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Foot positioning instruction, initial vertical load position and lifting technique: effects on low back loading

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Keywords: Lifting technique; Low back load; Ergonomics; Spine.

This study investigated the effects of initial load height and foot placement instruction in four lifting techniques: free, stoop (bending the back), squat (bending the knees) and a modified squat technique (bending the knees and rotating them outward). A 2D dynamic linked segment model was combined with an EMG assisted trunk muscle model to quantify kinematics and low back loading in 10 subjects performing 19 different lifting movements, using 10.5 kg boxes without handles. When lifting from a 0.05 m height with the feet behind the box, squat lifting resulted in 19.9% (SD 8.7%) higher net moments ($p < 0.001$) and 17.0% (SD 13.2%) higher compression forces ($p < 0.01$) than stoop lifting. This effect was reduced to 12.8% (SD 10.7%) for moments and a non-significant 7.4% (SD 16.0%) for compression forces when lifting with the feet beside the box and it disappeared when lifting from 0.5 m height. Differences between squat and stoop lifts, as well as the interaction with lifting height, could to a large extent be explained by changes in the horizontal L5/S1 intervertebral joint position relative to the load, the upper body acceleration, and lumbar flexion. Rotating the knees outward during squat lifts resulted in moments and compression forces that were smaller than in squat lifting but larger than in stoop lifting. Shear forces were small (< 300 N) at the L4/L5 joint and substantial (1100–1400 N) but unaffected by lifting technique at the L5/S1 joint. The present results show that the effects of lifting technique on low back loading depend on the task context.

1. Introduction

Mechanical loading of the low back has been shown to be an important risk factor for the development of low back pain (Norman *et al.* 1998). Manual materials handling, like lifting objects from the floor, causes compressive forces at the spine that could exceed the tolerance level of the intervertebral joints (Waters *et al.* 1993). Therefore, many ergonomic studies have investigated determinants of low back loading, usually by quantifying back loading in terms of net moments or compression forces. Knowledge about the effect of those determinants on low back loading could be used to develop effective preventive measures. For some determinants, like object weight (Davis and Marras 2000), lifting speed (Gagnon and Gagnon 1992, de Looze *et al.* 1994, Kingma *et al.* 2001), horizontal (Dolan *et al.* 1994, Ferguson *et al.* 2002) and vertical (Davis *et al.* 1998, Ferguson *et al.* 2002)

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position of the object relative to the worker, as well as several interactions between these factors (Lavender *et al.* 2003), substantial evidence has been presented showing their influence on lumbar loading (de Looze *et al.* 1994, Dolan *et al.* 1994, Kingma *et al.* 2001, Lavender *et al.* 2003).

One other factor that has been investigated in many studies is the lifting technique (for an overview, see van Dieën *et al.* 1999). Practitioners often recommend lifting objects by bending the knees (squat technique) rather than by bending the back (stoop technique). Early studies, using static biomechanical models (linked segment models) indeed suggested that lumbar spine loading was somewhat lower in squat lifting than in stoop lifting. However, dynamic linked segment models usually predict an equal or even higher lumbar load in squat lifting compared to stoop lifting (for an overview, see van Dieën *et al.* 1999). Lindbeck and Arborelius (1991) showed that, for the same data, a static analysis resulted in lower peak moments for stoop lifts whereas in a dynamic analysis moments tended to be higher in squat lifts. This suggests that accelerations, which are ignored in static models, are larger in squat lifting than in stoop lifting. Another reason could be that, in studies using static models and finding a lower back load in squat lifting, the feet were placed beside the load during squat lifting but not during stoop lifting (van Dieën *et al.* 1999).

Using dynamic linked segment models, the interaction between lifting technique and factors like lifting height or foot positioning has not yet been investigated. The aim of this study was therefore to establish the effect of foot placement instruction (i.e. an instruction to place the feet either behind or beside the load) and initial load height, both in squat lifting and in stoop lifting. In addition, since box size may interact with lifting technique and foot position, two boxes of different size but equal weight were used. Finally, the stoop and squat lifting techniques were compared with a free lifting technique and with a modified squat technique. The latter technique has, to the authors' knowledge, not been investigated as yet. In this technique, the feet are placed behind the load, and the feet and knees are rotated laterally. This technique might reduce the horizontal distance between the pelvis and the load. Lumbar loading was quantified using a dynamic 2D linked segment model to estimate net moments at the L5/S1 intervertebral joint. This model was coupled to an EMG driven detailed model of the trunk (van Dieën 1997, van Dieën *et al.* 2003) to estimate compressive and shear forces.

2. Methods

2.1. *Subjects*

Ten male subjects (age 22.3 ± 2.7 years, body height 1.83 ± 0.075 m, body weight 76.3 ± 8.1 kg) participated in the experiment after signing an informed consent form. None of the subjects had a history of low back pain.

2.2. *Experimental design*

All subjects performed two repetitions of lifting movements, differing in lifting technique (four techniques), foot placement instruction (three instructions), box size (two sizes) and initial height (two heights).

The four lifting techniques were a free technique, a stoop technique (lifting with the knees extended), a squat technique (bending the knees while holding the back as upright and straight as possible), and a modified squat technique. In the last technique, subjects were instructed to rotate their feet and knees about 45 degrees outward, and to maintain, if possible, a lumbar lordosis while lifting (see figure 1).

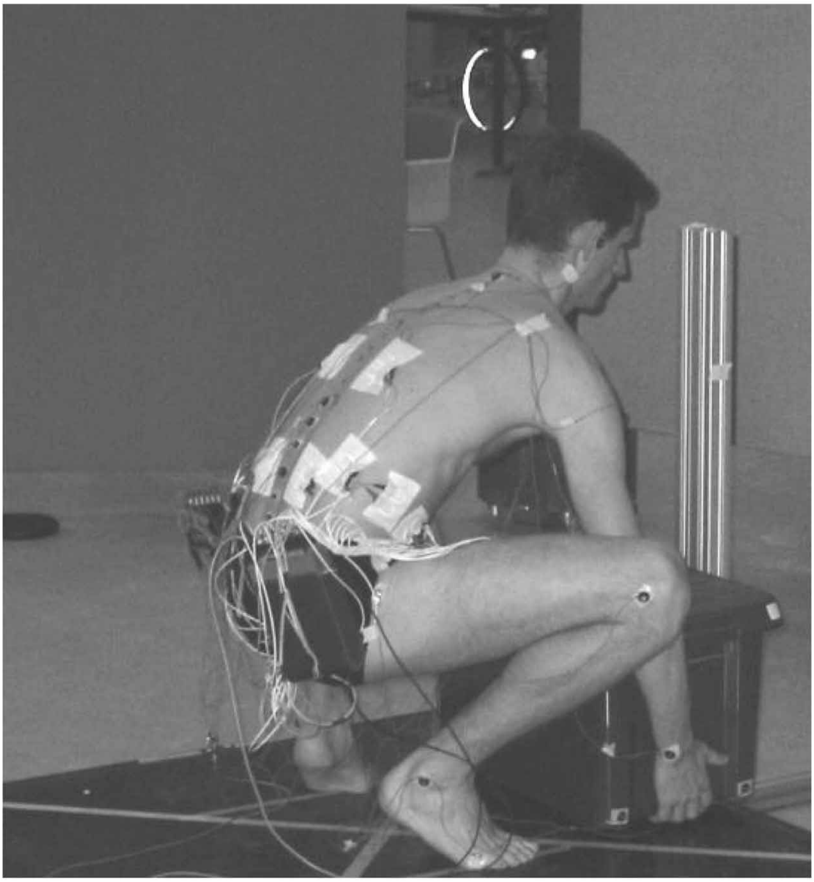

Figure 1. A photograph showing a subject lifting the large box using the modified squat lifting technique.

The two boxes were a large and a small box, both weighing 10.5 kg. The dimensions of the large and the small boxes were 330 × 230 × 200 mm and 480 × 340 × 330 mm (width × height × depth) respectively. The box dimensions were selected to allow easy (small box) and more difficult (large box) placement of the feet beside the box. The boxes had no handles. The two initial box heights were 0.05 and 0.5 m. Those heights were the heights of the bottom of the boxes (where the boxes were grasped). The three instructions on foot placement were: free, behind box (feet behind the box) and beside box (feet beside the box).

As will be discussed below, not all combinations of lifting technique, foot placement instruction, box height and box size were possible or considered relevant. As a result, a total number of 19 different lifts were performed (see table 1 for an overview). Foot placement instructions were only varied for the stoop and the squat technique. The free technique would not be free any more with a specific instruction on foot placement. The modified squat technique is not possible with the feet beside the box. Therefore, the free technique and the modified squat technique were only

Table 1. Overview of the lifting conditions used in this study. Nineteen conditions were included in the study, indicated by either a × or a ⊗. As indicated in the rows of the table, eight conditions were applied for lifts from 0.05 m with a free foot placement, four conditions were applied when lifting from 0.05 m with both a foot placement 'beside' the box and a foot placement 'behind' the box. Finally, three conditions were applied when lifting from 0.5 m with a free foot placement. ANOVAs were applied to three balanced subsets of conditions. The solid box includes conditions that were used in ANOVA 2. The dotted box includes conditions that were used in ANOVA 1. Conditions marked with a ⊗, rather than a ×, were included in ANOVA 3

		Free technique		Stoop technique		Squat technique		Modified squat technique	
Box size		Large box	Small box	Large box	Small box	Large box	Small box	Large box	Small box
Lift start height	Foot placement								
0.05 m	Free	⊗	×	⊗	×	⊗	×	×	×
0.05 m	Beside box			×	×	×	×		
0.05 m	Behind box			×	×	×	×		
0.5 m	Free	⊗		⊗		⊗			
0.5 m	Beside box								
0.5 m	Behind box								

performed with a 'free' foot placement. Furthermore, the modified squat technique is usually only instructed for lifts where objects have to be picked up from the floor. Therefore, the modified squat technique was only applied for the initial height of 0.05 m. Furthermore, lifting with the feet beside the box is not possible when the initial box height is 0.5 m. Therefore, this initial height was only applied with a 'free' foot placement. Finally, variations in box size were introduced specifically because box size might interact with foot placement instruction. Since foot placement was not varied with the 0.5 m initial box height, only one box size (the large box) was used when lifting from 0.5 m. Three ANOVAs were used on balanced subsets of conditions, to test the hypotheses that lifting technique affects spinal loads and kinematics in interaction with foot placement, box size, and initial box height.

2.3. *Procedure*

To standardize instruction, all techniques, except the free lifting technique, were explained with the aid of video. To prevent influence of previous instructions on the free lifting technique, the first technique was always a free technique. In the free technique subjects could place their feet where they liked and bend their knees as far as they liked. The subsequent 18 lifting conditions were performed in an order that was randomized for each subject.

Subjects were instructed to grasp the boxes at the bottom in a symmetrical way. The shape of the boxes allowed an easy and firm grip at the mid positions along the left and right bottom side. The initial box position for each lift was on a standard location on a shelf that was hanging above the (1.0 × 1.0 m) forceplate, on which the subject was standing. The boxes were lifted to a height that allowed the subject to stand upright with slightly flexed arms. After the recording stopped, the subject placed the box back on the shelf.

2.4. *Measurements and biochemical analyses*

Ground reaction forces were measured with a sampling rate of 75 Hz using a custom-made 1.0 × 1.0 m forceplate. This forceplate contains eight strain gauges: four to measure the vertical force in each corner and four to measure the horizontal force at each edge. The plate was calibrated with weights in the vertical direction and with a rope-and-pulley system in the horizontal direction. The error in the calculated point of application of the ground reaction force was < 4 mm. Movements of body segments were measured with a sampling rate of 75 Hz, and synchronized with forceplate signals, using an automated 3D movement registration system (Optotrak), with two arrays of three cameras. The frequency of 75 Hz was considered sufficient for the movement speed in lifting. LED markers were placed on the left side of the body at the foot (fifth metatarsal joint), the ankle (lateral malleolus), the knee (lateral epicondyle), the hip (greater trochanter), the L5/S1 joint (according to the procedure in de Looze *et al.* 1992), the spinous process at T1, the shoulder joint (just below the acromion), the elbow joint (lateral epicondyle) and the wrist joint. Furthermore, LED markers were placed on all spinal processes from T12 to S1. In addition, three LED markers were placed on each box.

A 2-D dynamic linked segment model was used to calculate net moments and reaction forces at the L5/S1 joint (de Looze *et al.* 1992). Segment inertial parameters were obtained according to Plagenhoef *et al.* (1983). A bottom-up inverse dynamic linked segment model was applied to calculate moments. Such a model uses ground reaction forces, and kinematics and anthropometry of the leg and pelvis. Using standard Newtonian mechanics, and assuming rigidity of the segments involved in the calculation, this procedure calculates net moment and reaction forces in subsequent joints.

Surface EMG electrodes were attached to the skin after abrasion and cleaning with alcohol (Ag/AgCl electrodes at an inter-electrode distance of 20 mm). Electrodes were bilaterally attached over two locations of the back muscles (3 cm lateral to L3 and 5 cm lateral to T10) and at five locations over the abdominal muscles: the internal oblique (dorsal and lateral), the external oblique (lateral and anterior) and rectus abdominis. EMG data were sampled at 1000 Hz and synchronized with forceplate and Optotrak recordings.

EMG data were high-pass filtered at a cut-off frequency of 10 Hz with a 2nd order Butterworth filter, rectified, and low-pass filtered with a cut-off frequency of 2.25 Hz with a 2nd order Butterworth filter. Subsequently, EMG signals were normalized to maximum voluntary contractions (defined as the two seconds of maximum activation for each muscle from a series of maximum voluntary extensions, flexions, lateral flexions and torsions) and used as input to an EMG driven trunk muscle model. The model has previously been described in more detail (van Dieën 1997, van Dieën *et al.* 2003) and consists of a compilation of anatomical data described by Stokes and Gardner-Morse (1995) for the back muscles and by McGill and Norman (1985) for the abdominal muscles. The transversus abdominis and the psoas major muscle were excluded because it is unlikely that their activity can reliably be estimated from surface EMG and because their moment-producing capacity is limited. The latissimus dorsi muscle was omitted because a reliable indication of its force would require modelling the shoulder in detail and because its capacity to generate an extensor moment at the lumbar spine is only very small (Bogduk *et al.* 1998). After exclusion of the above-mentioned muscles, the model consisted of 90 muscle slips crossing the L5/S1 joint. The model was scaled to individual body height. 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.

Because of the symmetry of the lifting movements, left and right EMG signals were averaged before assigning each of the 90 muscle slips to one of the EMG signals. Muscle forces were estimated as the product of the maximum muscle stress (a single value for all muscles that was adjusted for each subject to obtain the best fit between net moments and muscle moments), normalized EMG amplitude and correction factors for the instantaneous muscle length (Woittiez *et al.* 1984) and contraction velocity (van Zandwijk 1998). The muscle lengths and contraction velocities were calculated on the basis of the lumbar flexion. The lumbar flexion was defined as the angle of a line through the markers on L5 and S1 with a line through the markers on T12 and L1. To obtain compression and shear forces at the L5/S1 intervertebral disc, muscle forces and net reaction forces were summed after projecting them on the axis system connected to the middle of the L5/S1 disc. To obtain shear forces at the L4/L5 joint, muscle forces and net reaction forces were projected on the axis system connected to the middle of the L4/L5 disc.

2.5. *Statistical analysis*

The dependent variables that were statistically analysed were: peak net moments, peak compression and forward shear forces at the L5/S1 joint, peak forward shear forces at the L4/L5 joint, and peak lumbar flexion. In addition, at the instant of peak

Table 2. Results of three repeated-measures ANOVAs applied to balanced subsets of lifts using a 10.5 kg box. The lifting movements varied in lifting technique, foot positioning instruction, initial box height and box size. Significant effects ($p < 0.05$) are indicated by bold values.

			Peak forward shear force					At instant of peak L5/S1 compression	
	Peak compression	Peak net moment	L5/S1 Ftotal	L5/S1 Freaction	L5/S1 Fmuscular	L4/L5 Ftotal	Peak lumbar flexion	L5/S1 position	Total net reaction force
	p	p	p	p	p	p	p	p	p
ANOVA 1									
box (large, small)	**0.046**	< **0.001**	0.105	**0.031**	0.366	**0.015**	**0.013**	**0.003**	< **0.001**
technique (St, Sq)[1]	**0.004**	< **0.001**	0.301	< **0.001**	**0.001**	< **0.001**	**0.001**	**0.001**	**0.005**
foot (free, beside, behind)	**0.002**	< **0.001**	0.916	0.601	0.599	**0.009**	0.609	< **0.001**	**0.030**
box*technique	0.482	**0.033**	**0.019**	0.563	**0.017**	**0.038**	**0.037**	0.072	0.127
box*foot	0.102	0.273	0.470	0.248	0.295	0.401	0.055	0.380	0.190
foot*technique	< **0.001**	< **0.001**	0.450	**0.030**	0.386	0.199	0.787	0.067	0.322
box*technique*foot	0.589	0.482	0.112	0.171	0.179	0.505	0.510	0.876	0.915
ANOVA 2									
box (large, small)	0.084	< **0.001**	0.141	0.079	0.623	0.303	**0.016**	**0.003**	**0.007**
technique (St, Sq, Msq, Fr)[1]	< **0.001**	< **0.001**	0.088	< **0.001**	< **0.001**	< **0.001**	< **0.001**	< **0.001**	< **0.001**
box*technique	0.061	0.065	**0.024**	0.352	**0.029**	0.070	0.066	0.358	0.533
ANOVA 3									
height (0.05 m, 0.5 m)	< **0.001**	< **0.001**	0.302	**0.013**	0.995	**0.002**	< **0.001**	**0.003**	0.133
technique (St, Sq, Fr)[1]	**0.019**	**0.031**	0.088	< **0.001**	< **0.001**	< **0.001**	< **0.001**	**0.002**	**0.001**
height*technique	**0.006**	< **0.001**	0.437	**0.009**	**0.041**	**0.007**	**0.004**	**0.015**	**0.023**

[1] St = stoop technique, Sq = squat technique, Msq = modified squat technique, Fr = free technique.

compression force, the values of the following variables were used as dependent variables: total net reaction forces (i.e., the vector sum of the forward–backward and upward component) at the L5/S1 joint, and the location of the L5/S1 joint.

Because the design of the complete experiment was not balanced, repeated-measures ANOVAs were applied to three balanced subsets of the data. The foot placement instruction had only been varied in squat and stoop lifts from 0.05 m. Therefore, the first ANOVA used lifting technique (two levels), foot placement instruction (three levels) and box size (two levels) as independent variables. Because the modified squat technique was only applied with a free foot placement and 0.05 m vertical load position, the second ANOVA (aiming to compare the four lifting

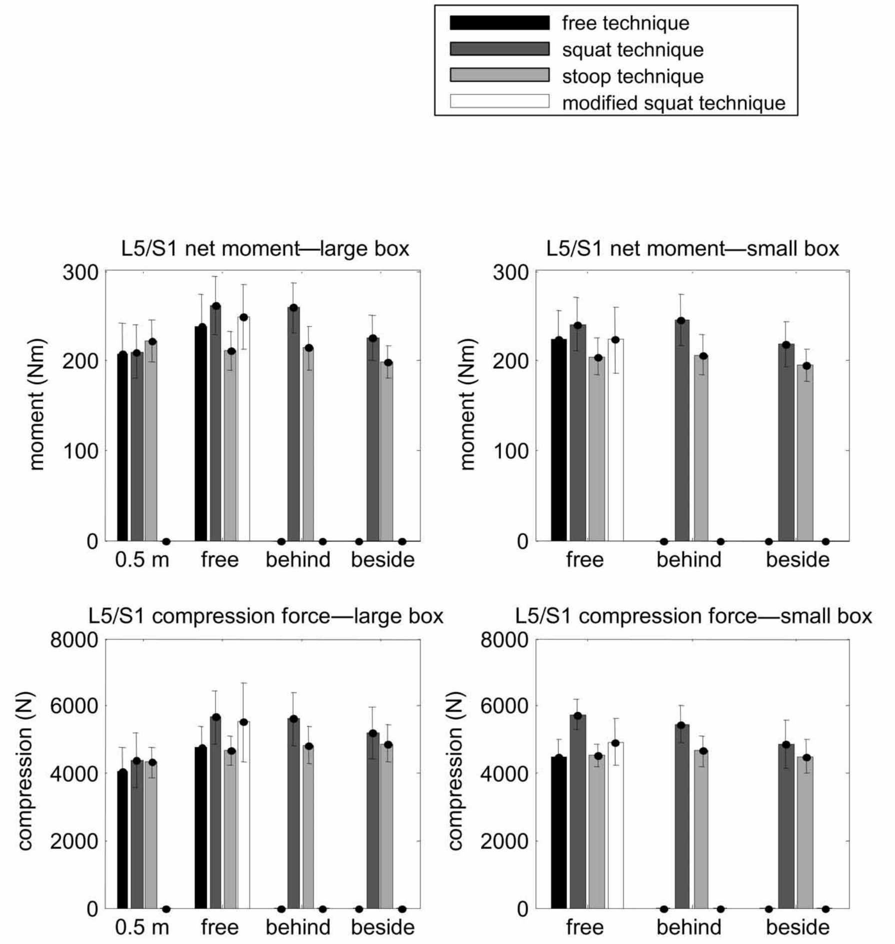

Figure 2. Peak net moments (top) and compression forces (bottom) in lifting a large (left) and a small (right) 10.5 kg box. On the horizontal axis, the box location relative to the feet is indicated: 0.5 m means 0.5 m initial height with free foot placement; free, behind and beside are the instructed foot placements in lifts from a height of 0.05 m. Error bars indicate one standard deviation.

techniques) used only the lifts from the 0.05 m height and only the free foot placement. The independent variables were: lifting technique (four levels) and box size (two levels). Lifts from 0.5 m had only been performed with the large box, a free foot placement instruction and three lifting techniques (squat, stoop and free). Therefore, a third ANOVA was applied with box height (two levels) and lifting technique (three levels) as independent variables, using only the large box and free foot placement instruction. For independent variables with more than two levels, post-hoc comparisons between pairs of variables were made using paired t-tests.

3. Results

The results of the three repeated-measures ANOVAs for each of the dependent variables are given in table 2 and explained in more detail in the following sections. Values in the text are given as means and standard deviations.

3.1. *Peak moments and compression forces at the L5/S1 joint*

When comparing the pattern of low back loading over all lifting conditions (figure 2), net moments and L5/S1 compression forces showed similar tendencies. For net moments as well as compression forces, ANOVA 1, testing all squat and stoop lifts from 0.05 m, showed significant effects of box size, foot placement instruction, lifting technique, and interaction between foot placement instruction and lifting technique (table 2). Over both boxes and all three foot placement instructions, squat lifting resulted in 17.8 ± 9.4% higher moments and 16.0 ± 13.2% higher compression forces than stoop lifting. Furthermore, the instruction to lift with the feet beside the box resulted in lower moments (9.4 ± 3.4%) and compression forces (5.3 ± 5.1%) as compared to the instruction to lift with the feet beside the box. The difference between squat and stoop lifting was larger when lifting with the feet behind the box (19.9 ± 8.7% for moments and 17.0 ± 13.2% for compression forces) than when lifting with the feet beside the box (12.8 ± 10.7% for moments and a non-significant difference of 7.4 ± 16.0% for compression forces). Note that when lifting with the feet beside the box, moments as well as compression forces remained higher in squat lifts than in stoop lifts (though this was not significant for compression forces) (table 3). When subjects were free to place their feet relative to the box, they always lifted with the feet behind the box. This was even the case when they had received explicit instructions to lift with the feet beside the box in previous lifts. Consequently, low back loading in terms of net moments and compression forces did not differ between a free foot placement and the instruction to lift with the feet behind the box (post-hoc test ANOVA 1, see table 3).

ANOVA 3 (comparing free, stoop and squat lifts from 0.05 m and 0.5 m) showed that, besides a main effect of lifting technique, there was an interaction between lifting height and lifting technique (table 2). When lifting from 0.5 m, the difference between squat and stoop lifts was no longer significant for compression forces, and even turned into a slight (5.3 ± 5.9%) but significant advantage in squat lifts for net moments (*post hoc* test ANOVA 3, see table 3).

The modified squat technique had only been applied with the feet behind the box in lifts from 0.05 m. ANOVA 2, comparing four lifting techniques with two box sizes when lifting with a free foot placement from 0.05 m, showed a main effect of lifting technique (table 2). The modified squat technique (see figure 2 and *post-hoc* tests of ANOVA 2, table 3) resulted in net moments and compression forces that were lower than in squat lifting (6.0 ± 6.4% for moments and 8.1 ± 9.1% for compression

Table 3. *Post-hoc* test results related to ANOVAs 1 – 3. *Post hoc* tests were performed for all significant interactions (see table 2) and for main effects with more than two levels where interactions with this main effect were not significant.

						Peak forward shear force					At instant of peak L5/S1 compression	
				Peak compression	Peak moment	L5/S1 Ftotal	L5/S1 Freaction	L5/S1 Fmuscular	L4/L5 Ftotal	Peak lumbar flexion	L5/S1 position	L5/S1 total net force
ANOVA 1												
effect	*box*	*feet*[1]	*tech*[2]									
foot	both	**free-beh**	sq + st						0.836		0.764	0.288
foot	both	**free-bes**	sq + st						0.013		< 0.001	0.004
foot	both	**beh-bes**	sq + st						0.020		< 0.001	0.139
foot*tech	both	free	**sq-st**	< 0.001	< 0.001		< 0.001					
foot*tech	both	beh	**sq-st**	0.003	< 0.001		< 0.001					
foot*tech	both	bes	**sq-st**	0.178	0.004		0.010					
box*tech	large	all	**sq-st**		< 0.001	0.533		0.001	< 0.001	0.004		
box*tech	small	all	**sq-st**		0.001	0.171		< 0.001	< 0.001	0.001		
ANOVA 2												
effect	*box*	*feet*	*tech*									
tech	both	free	**fr-sq**	< 0.001	0.034		0.146		0.017	0.198	0.003	0.495
tech	both	free	**fr-st**	0.941	0.012		0.001		< 0.001	0.012	0.326	0.003
tech	both	free	**fr-msq**	0.034	0.458		0.547		0.345	0.028	0.359	0.249
tech	both	free	**sq-st**	< 0.001	< 0.001		< 0.001		< 0.001	0.001	< 0.001	0.003
tech	both	free	**sq-msq**	0.020	0.016		0.154		0.052	0.258	< 0.001	0.289
tech	both	free	**st-msq**	0.025	0.007		< 0.001		< 0.001	0.001	0.700	0.002
box*tech	large	free	**fr-sq**			0.191		0.001				
box*tech	large	free	**fr-st**			0.099		0.284				
box*tech	large	free	**fr-msq**			0.068		0.004				
box*tech	large	free	**sq-st**			0.913		< 0.001				
box*tech	large	free	**sq-msq**			0.208		0.415				
box*tech	large	free	**st-msq**			0.214		0.002				
box*tech	small	free	**fr-sq**			0.047		0.001				

(*continued overleaf*)

Table 3. (*continued*)

						Peak forward shear force					At instant of peak L5/S1 compression	
				Peak compression	Peak moment	L5/S1 Ftotal	L5/S1 Freaction	L5/S1 Fmuscular	L4/L5 Ftotal	Peak lumbar flexion	L5/S1 position	L5/S1 total net force
box*tech	small	free	**fr-st**			0.365		0.320				
box*tech	small	free	**fr-msq**			0.059		< 0.001				
box*tech	small	free	**sq-st**			0.161		0.001				
box*tech	small	free	**sq-msq**			0.537		0.126				
box*tech	small	free	**st-msq**			0.092		< 0.001				
ANOVA 3 (large box only)												
effect	*height*	*feet*	*tech*									
height*tech	0.05	free	**fr-sq**	0.001	0.015		0.124	0.001	0.383	0.528	0.014	0.278
height*tech	0.05	free	**fr-st**	0.629	0.005		0.001	0.284	0.001	0.018	0.230	0.003
height*tech	0.05	free	**sq-st**	0.003	< 0.001		< 0.001	< 0.001	< 0.001	0.001	< 0.001	0.001
height*tech	0.5	free	**fr-sq**	0.217	0.736		0.700	0.002	0.070	0.009	0.006	0.021
height*tech	0.5	free	**fr-st**	0.293	0.152		0.003	0.025	0.024	0.416	0.418	0.771
height*tech	0.5	free	**sq-st**	0.799	0.019		< 0.001	0.029	0.008	0.002	0.050	0.057

[1]free = free foot position, beh = feet behind the box, bes = feet beside the box. [2]St = stoop technique, Sq = squat technique, Msq = modified squat technique, Fr = free technique.

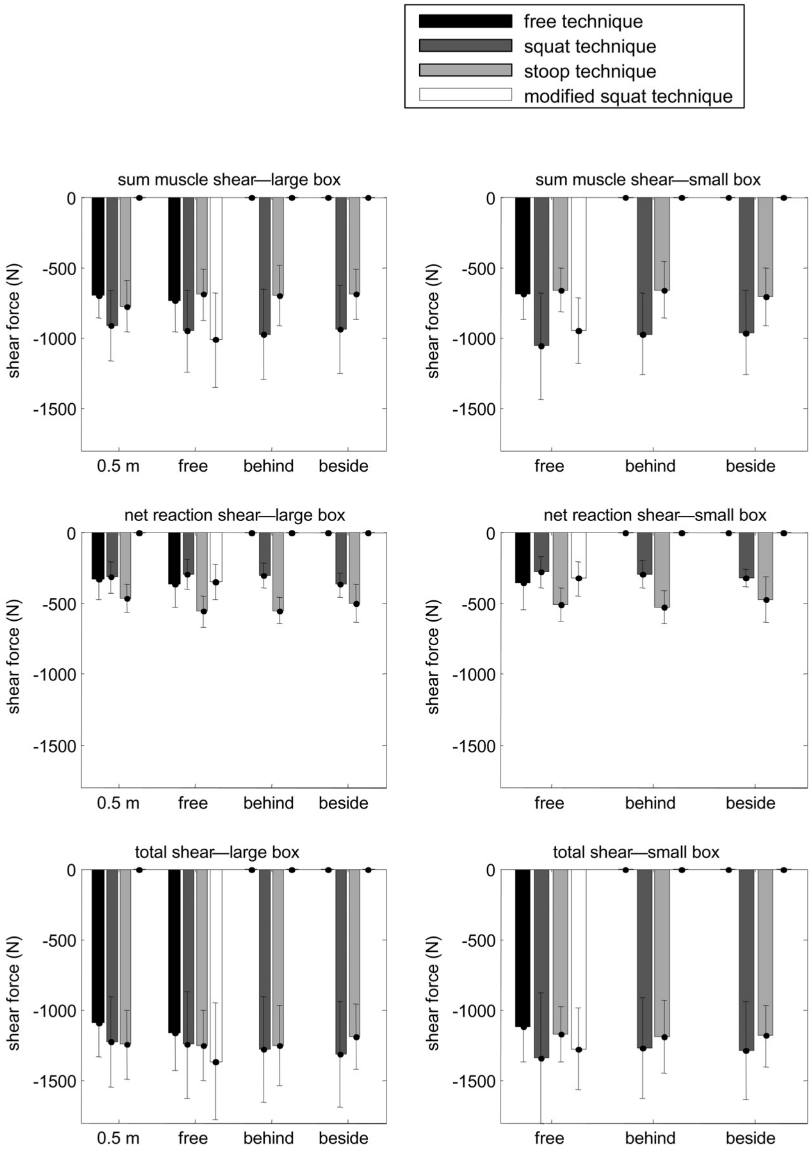

Figure 3. Muscular component (top), net reaction force component (middle) and their sum, which is the peak total shear force (bottom) at the L5/S1 joint in lifting a large (left) and a small (right) 10.5 kg box. Negative values are forward shear forces. On the horizontal axis, the box location relative to the feet is indicated: 0.5 m means 0.5 m initial height with free foot placement; free, behind and beside are the instructed foot placements in lifts from a height of 0.05 m. Error bars indicate one standard deviation.

forces) but higher than in stoop lifting (13.2 ± 12.0% for moments and 13.6 ± 16.0% for compression forces).

The free lifting technique typically resulted in lifts that can be considered as an intermediate technique, in between squat and stoop lifts (figure 2). Therefore, it is

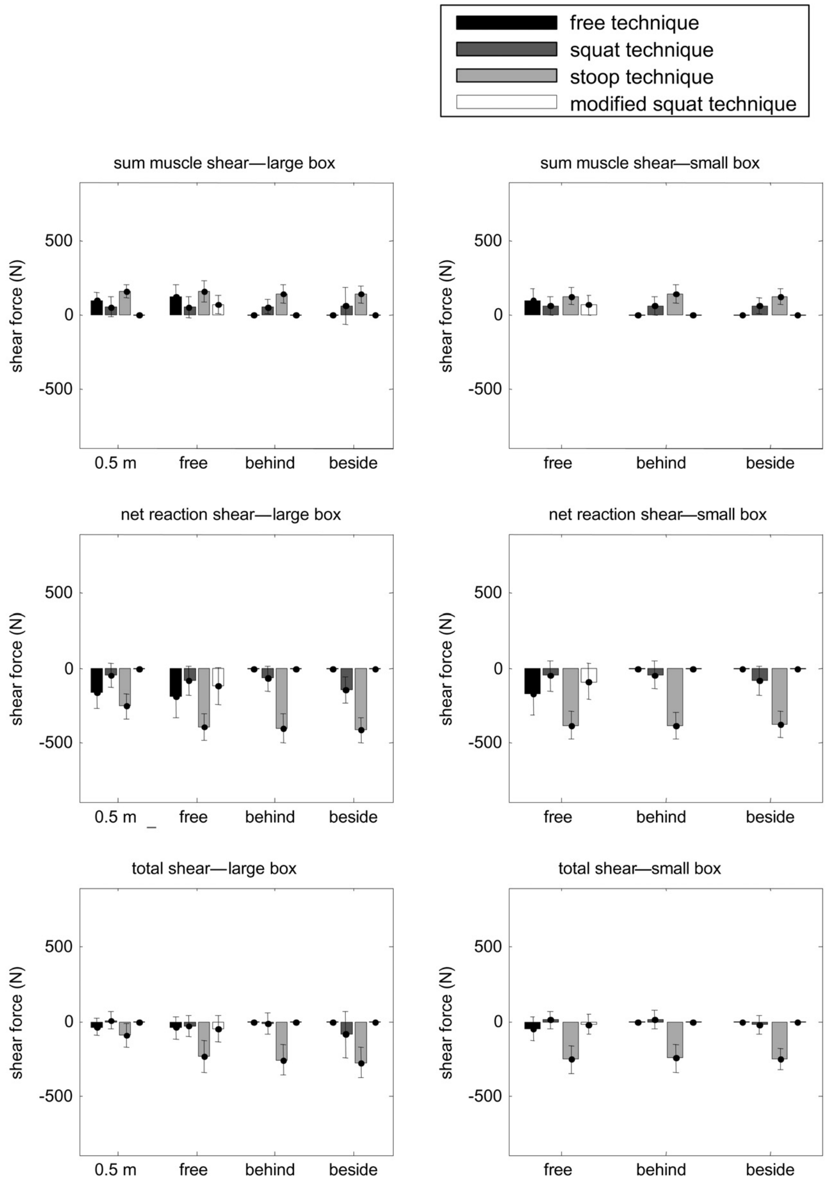

Figure 4. Muscular component (top), net reaction force component (middle) and their sum, which is the peak total shear force (bottom) at the L4/L5 joint in lifting a large (left) and a small (right) 10.5 kg box. Negative values are forward shear forces. On the horizontal axis, the box location relative to the feet is indicated: 0.5 m means 0.5 m initial height with free foot placement; free, behind and beside are the instructed foot placements in lifts from a height of 0.05 m. Error bars indicate one standard deviation.

not surprising that free lifts, like the modified squat technique, resulted in net moments and compression forces in between squat and stoop lifts. However,

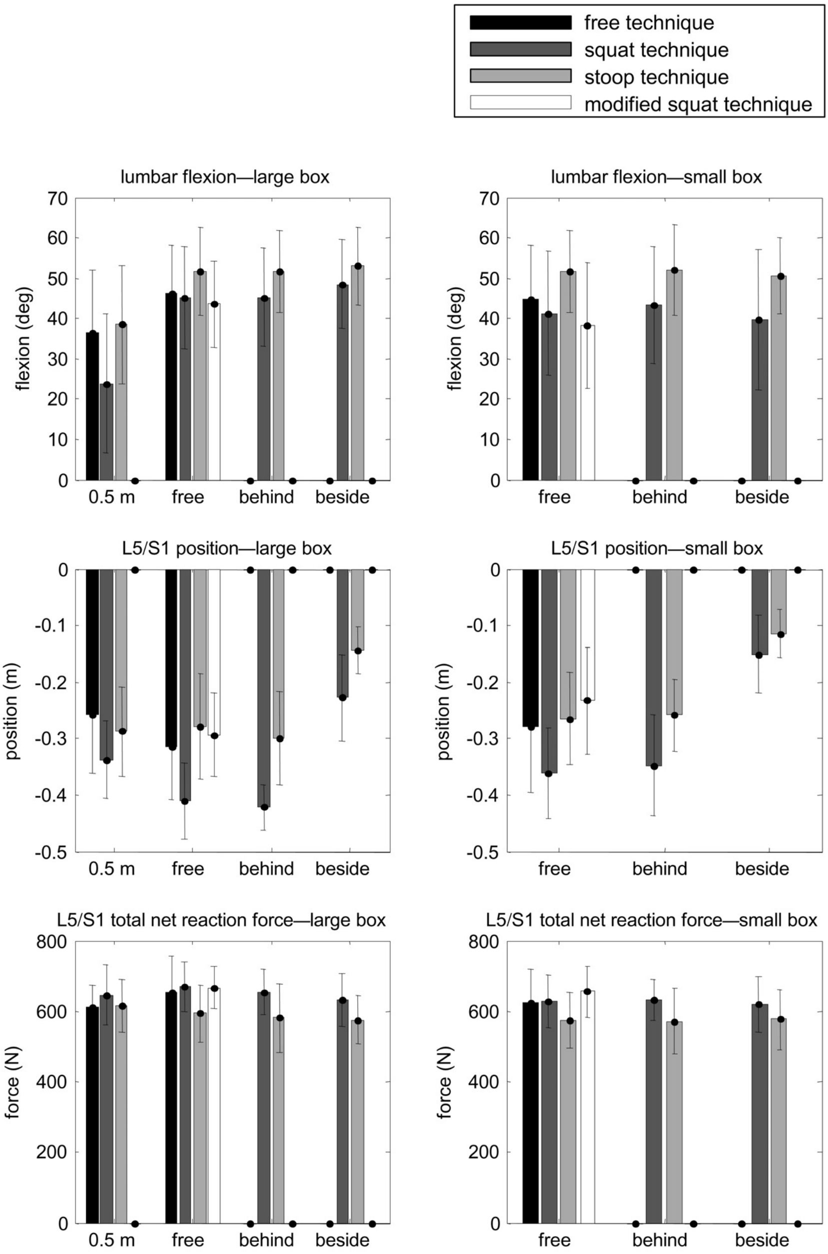

Figure 5. Peak lumbar flexion angle (top), forward–backward L5/S1 position at the instant of peak compression (middle), and total net reaction force at the L5/S1 joint at the instant of peak compression (bottom) in lifting a large (left) and a small (right) 10.5 kg box. On the horizontal axis, the box location relative to the feet is indicated: 0.5 m means 0.5 m initial height with free foot placement; free, behind and beside are the instructed foot placements in lifts from a height of 0.05 m. Error bars indicate one standard deviation.

compression forces in the free lifting technique did not significantly differ from squat lifts (*post-hoc* tests of ANOVA 2, table 3).

3.2. *Peak shear forces at the L5/S1 and L4/L5 joints*

At the L5/S1 joint, the total shear force (figure 3 and table 2) was not significantly affected by instruction on foot placement (ANOVA 1) or initial lifting height (ANOVA 3). Lifting technique effects were non-significant (ANOVAs 1, 2 and 3), although a tendency was found ($p = 0.088$) that mainly consisted of a reduced shear force in the free lifts (ANOVAs 2 and 3). The non-significance of this tendency could have been due to a high between-subject variance of the shear forces. The only significant effect was a slight but significant interaction between box size and lifting technique. However, when the total shear force was decomposed into a muscular and a reaction force component, highly significant effects of lifting technique as well as some interactions with lifting technique, were found for both components (ANOVAs 1, 2 and 3; table 2). For the muscular component, shear forces were larger in squat lifting and for the reaction force component shear forces were larger in stoop lifting. Those effects appeared to cancel each other.

At the L4/L5 joint, box size (ANOVA 1), lifting technique (ANOVAs 1, 2 and 3) instructions on foot placement (ANOVA 1) as well as initial box height (ANOVA 3) significantly affected the peak total forward shear force (table 2). However, the peak forward shear forces were much smaller in the L4/L5 joint than in the L5/S1 joint (figure 4). This was mainly due to the fact that, at the instant of peak forward shear force, the muscular component of the shear force was still backward in the L4/L5 joint. The resulting shear forces were in fact only substantial in the stoop lifting technique (255 ± 29 N). However, those forces were still almost five times smaller than at the L5/S1 joint in the same lifts (1239 ± 90 N).

3.3. *Trunk angle*

Not surprisingly, main effects of lifting technique (ANOVAs 1, 2 and 3) and initial box height (ANOVA 3) on the peak lumbar flexion during lifting were significant (figure 5 and table 2). In addition, there was a small ($< 3^\circ$) but significant effect of box size (ANOVAs 1 and 2). The instruction on foot placement did not significantly affect lumbar flexion. With respect to the lifting technique, the difference in lumbar flexion between squat and stoop lifts, averaged over all instructions on foot placement and both boxes, was $7.9 \pm 5.3^\circ$. Lifting technique interacted with box height (ANOVA 3) in that the difference between squat and stoop lift increased when lifting from 0.5 m. The lumbar flexion in the modified squat technique did not differ significantly from the squat lifts (post hoc test after ANOVA 2, see table 3).

3.4. *L5/S1 position at peak compression*

The smaller lumbar flexion in squat lifts compared to stoop lifts appears at odds with the higher moments and compression forces in squat lifts than in stoop lifts. Therefore, two additional kinematics variables were analysed, in order to explain the effects of lifting technique on low back loading. The first of these variables was the forward–backward L5/S1 position during peak compression. Since the initial box position was constant in the horizontal direction, a change in L5/S1 position during peak compression implies a change of the moment arm of the box relative to L5/S1. The second variable is the vector sum of the horizontal and vertical component of the net reaction force at the L5/S1 joint during peak compression. This force is directly related to the acceleration of the upper body plus box.

The L5/S1 position at the instant of peak compression was slightly but significantly affected by box size (ANOVAs 1 and 2) and initial lifting height (ANOVA 3). More importantly, major effects on the L5/S1 position were found for foot positioning instruction (ANOVA 1) and lifting technique (ANOVAs 1, 2 and 3). As might be expected, the L5/S1 position was more forward (0.173 ± 0.043m), and thus closer to the box, when subjects were instructed to lift with feet beside the box than when instructed to lift with the feet behind the box (figure 5). Interestingly, L5/S1 at the instant of peak compression was 0.093 ± 0.053 m more backward in squat lifting than in stoop lifting. Since the initial box position was the same, this implies a larger moment arm of the box relative to the low back in squat lifting, which is thus in part responsible for the higher low back loading in squat lifting than in stoop lifting.

The difference in L5/S1 position between squat and stoop lifting tended to be somewhat smaller when lifting with the feet beside the box compared to lifting with the feet behind the box. However, the interaction between instruction on foot placement and lifting technique did not reach significance (ANOVA 1, $p = 0.067$).

Lifting technique interacted with box height (ANOVA 3). At 0.5 m, the difference between the squat and stoop lifts with regard to the L5/S1 position was reduced to 0.05 ± 0.07 m, and was borderline significant (*post hoc* test, $p = 0.050$). This less pronounced difference in L5/S1 position when lifting from 0.5 m would reduce low back loading in squat lifting compared to stoop lifting, which was indeed the effect that was found (see above).

The modified squat technique was intended to bring the pelvis closer to the box as compared to the squat lifts. This was successful in that the L5/S1 joint was indeed 0.123 ± 0.0067 m (post hoc test after ANOVA 2 , see Table 3) closer to the box in the modified squat technique than in the squat technique. However, the L5/S1 joint position at the instant of peak compression did not differ significantly from that in the stoop technique.

3.5. *Total net reaction force at the L5/S1 joint*

The total net reaction force at the L5/S1 joint at the instant of peak compression, which represents forces due to the upper body (and box) weight plus acceleration, showed small but significant main effects of box size (ANOVA 1) and of instruction on foot placement (ANOVA 1). More substantial effects (figure 5) were found for lifting technique (ANOVAs 1, 2 and 3). Averaged over both boxes and all three instructions on foot placement, these forces were 60 ± 52 N higher in squat lifting than in stoop lifting. Since larger upper body accelerations increase low back loading, this difference in reaction forces is in part responsible for the higher low back loading in squat lifts.

Lifting technique interacted with box height (ANOVA 3), in that the difference between squat and stoop techniques was smaller when lifting from 0.5 m. This is consistent with the disappearing effect of lifting technique on low back loading when lifting from 0.5 m.

Lifting technique did not interact significantly with instruction on foot placement (ANOVA 1). The modified squat technique resulted in a total net reaction force that was not significantly different from squat lifts but 75 ± 57 N higher than in the stoop lifts (*post hoc* test after ANOVA 2, see table 3).

4. Discussion

This study compared low back loading over four different lifting techniques, and investigated the effect of foot positioning instruction and initial vertical load position on low back loading in squat and stoop lifting. As has been reported before, low back loading was found to be lower when lifting with the feet beside the box than when lifting with the feet behind the box (e.g. Dolan *et al.* 1994), lower when lifting from a high initial position than when lifting from a low initial position (e.g. Lavender *et al.* 2003), and lower in stoop lifting than in squat lifting (e.g. de Looze *et al.* 1998, Kingma *et al.* 2001). However, the present study also found a strong interaction of stoop versus squat lifting with initial box height. When lifting from 0.05 m, low back loading was substantially higher in squat lifting than in stoop lifting, but this effect completely disappeared when lifting from 0.5 m. In the current study, subjects grasped the boxes at the bottom, so that, when lifting from 0.05 m, the initial hand position was lower than in some previous studies (Potvin *et al.* 1991a, de Looze *et al.* 1992, 1998, Kingma *et al.* 2001). Therefore, the interaction between lifting technique and lifting height may also explain why the difference between stoop and squat techniques (in lifts from 0.05 m) was more pronounced in this study as compared to those previous studies. The cause of the interaction between lifting technique and lifting height can be understood from the kinematic variables that were quantified in this study. In lifting from 0.05 m, peak moments and compression forces were substantially higher in squat lifting than in stoop lifting due to a more backward L5/S1 position and more upper body acceleration. In lifting from 0.5 m, both variables showed an effect towards a reduced difference between squat and stoop lifting. Both effects will reduce low back loading in squat lifting relative to stoop lifting. A third effect with the same consequence was the more pronounced difference in lumbar flexion between squat and stoop lifting when lifting from 0.5 m. The relatively small difference in lumbar flexion between stoop and squat lifting when lifting from 0.05 m might be explained by the hip flexion, which is likely to reach its maximum when lifting from 0.05 m using the squat technique. This may force a backward rotation of the pelvis in low squat lifts, resulting in enhanced lumbar flexion. When lifting from 0.5 m, the absence of full hip flexion may thus explain the more pronounced difference in lumbar flexion between stoop and squat lifting.

Similarly to increasing the initial box height, lifting with the feet beside the box rather than with the feet behind the box reduced the difference in back loading between squat and stoop lifts. However, this effect was less pronounced than the effect of initial box height, since moments and compression forces were still higher in squat lifts than in stoop lifts (although this was not significant for compression forces) when lifting with the feet beside the box. Underlying kinematic variables did not show significant interactions between lifting technique and instruction on foot placement. However, based on the close to significant tendency, the forward-backward L5/S1 position seems to be the most likely cause of a reduced difference between squat and stoop lifting when lifting with the feet beside the box.

The modified squat technique was intended to reduce low back loading during squat lifting by rotating the feet and knees outward, thereby bringing the pelvis close to the load. Indeed this technique was found to reduce low back loading, but not below the level that is obtained during stoop lifting. In fact, despite an L5/S1 position that was comparable to stoop lifts and a lumbar flexion that was reduced in comparison to stoop lifts, moments and compression forces were higher in the modified squat technique than in stoop lifting. The main cause of this higher back loading in the modified squat technique appears to be the larger acceleration of the upper body at the instant of peak compression.

At the L4/L5 joint, Potvin *et al.* (1991b) predicted, for squat lifting, quite small shear forces (below 200 N), which is comparable to the present findings. In line with Potvin *et al.* (1991a) substantially larger forward shear forces at the L4/L5 joint were found in stoop lifting as compared to squat lifting. However, those forces were still almost five times smaller than at the L5/S1 joint.

The large differences in shear forces between the L5/S1 and L4/L5 joints can be understood from the orientation difference between L5 and S1. In the model, L5/S1 is oriented 27.2° more forward than L4/L5 in the neutral posture. Full flexion was on average slightly over 50° in stoop lifts. Since this flexion is distributed over the lumbar intervertebral joints, L5/S1 remains about 17° more forward-oriented than L4/L5, even in full flexion. When it is assumed that the orientation of the muscles crossing both joints does not change between the L4/L5 and L5/S1 joint, this means that the muscle force vector changes with an angle of 17° between L5/S1 and L4/L5. With a muscle force of 5000 N this would be equivalent to a change in shear force of over 1400 N. Since the orientation difference between L5/S1 and L4/L5 also causes the reaction force component of the forward shear force to be larger in L5/S1 than in L4/L5, quite large forward shear forces at the L5/S1 joint are not unexpected. The order of magnitude of shear forces in the L5/S1 joint was quite comparable with previous studies using EMG assisted (not single equivalent) trunk muscle models (Kingma and van Dieen 2004, Granata *et al.* 1999, Ferguson *et al.* 2002).

The muscular component of the forward shear forces at the L5/S1 joint was larger for squat lifting than for stoop lifting. This can be understood from the fact that muscle forces were substantially greater in squat lifting than in stoop lifting and that the difference in lumbar flexion between squat lifting and stoop lifting was less than 10°. Since this flexion difference is distributed over the intervertebral joints, the difference in flexion between squat and stoop lifts is only about 2° at the L5/S1 joint. This small difference only slightly changes the line of action of the muscles relative to the joint. In contrast to the muscular component, the net reaction force component of the shear force at the L5/S1 joint was larger for stoop lifting. This is most likely due to the more forward-inclined orientation of the L5/S1 joint in stoop lifts. When the muscular component and the net reaction force component of the shear forces were summed to obtain the total shear force, the effects of lifting technique were no longer significant.

Some limitations of this study should be mentioned. First, lifting techniques were imposed by instruction. In practice, subjects generally do not apply a pure stoop or squat technique when lifting objects from a position close to the floor (Burgess-Limerick *et al.* 1995). No reports were found on the amount of outward knee rotation, but it is likely that, especially after having received lifting instructions, many subjects will tend to lift more like the modified squat technique than like the squat technique. In addition, the self-selected lifting technique was reported to vary with object height, with lower objects resulting in squat-like lifts and higher objects resulting in stoop-like lifts (Burgess-Limerick *et al.* 2001). Second, the present study only investigated one, relatively light load (10.5 kg). However, a review of stoop and squat lifts showed that, over a wide range of load masses, similar effects of lifting technique are reported (van Dieën *et al.* 1999). Third, lumbar flexion was measured on the basis of skin markers at the spinal processes. This method has not specifically been validated. However, it has been shown that the positions of the centres of vertebral bodies are strongly (though not necessarily linearly) related to skin marker positions (Lee *et al.* 1995, Sicard and Gagnon, 1993).

Another limitation of the current study is that it only looked at symmetrical lifting. In a survey of industrial lifting, Dempsey (2003) showed that the 50th percentile of lifting movements contains 10° asymmetry with respect to the origin and 15° of asymmetry with respect to the destination. Thus, roughly half of the industrial lifts contain only a small amount of asymmetry, whereas the other half is more asymmetrical. Therefore, studying symmetrical lifting is relevant to about half of industrial lifting tasks.

The lifts in the current study may not have been perfectly symmetrical. It could therefore be argued that a 3D approach would be more appropriate for this study. However, in a previous study, the authors showed that, up to 10° of asymmetry, differences between a 3D and a 2D model are not significant (Kingma *et al.* 1998). Considering the (instructed) symmetrical foot placement in this study, combined with the (instructed) symmetrical way in which the boxes were grasped, 10° of asymmetry is unlikely to have been exceeded in this study.

Some other limitations are that this study investigated only two lifting heights, and tested a relatively small number of subjects from only one gender. It could well be that other lifting heights would result in other differences between squat and stoop lifts. Furthermore, females may show a low back loading pattern that differs from males, since kinematics in squat and stoop lifts were reported to differ between males and females (Lindbeck and Kjellberg 2001), and spinal compression was reported to be affected by an interaction between gender and lifting height (Marras *et al.* 2003). The relatively small number of subjects limits the statistical power, and more subtle effects could show up with a larger group of subjects. Furthermore, subjects from another population with, for instance, more mobile hip joints could show a deviating pattern of joint loading, because large hip flexions are reached in squat lifts, which suggests that the actual implementation of the technique might be affected by the hip flexion range.

With respect to lifts from 0.5 m, the present results can be interpreted as favouring squat lifting over stoop lifting because net L5/S1 moments as well as lumbar flexion were smaller in squat lifts than in stoop lifts. When lifting from 0.05 m, L5/S1 moments and compression forces were higher in squat lifting than in stoop lifting, without a significant reduction in shear forces. Therefore, this study, in accordance with three recent reviews comparing stoop to squat lifts (Straker 2003, Burgess-Limerick 2003, van Dieën *et al.* 1999), does not support the advice to use the squat lifting technique for low-lying objects. However, the current results should not be interpreted as an argument to favour lifting with fully extended knees, when lifting an object from the floor. In such situations, full lumbar flexion may be attained, resulting in substantial stresses on vertebral ligaments (Adams *et al.* 1994a). In addition, Adams *et al.* (1994b) reported a reduced compressive strength beyond 75% of the maximum *in vitro* flexion. However, according to Adams and Hutton (1986) it is unlikely that such flexions are reached *in vivo*. With respect to foot placement, the current study reinforces the advice to lift with the feet beside the load when lifting from the ground and to lift preferably from higher positions than from the ground. Finally, the current results do support the view that the modified squat technique is to be preferred over the squat technique, since it reduces moments and compression forces without increasing trunk flexion or shear forces.

In conclusion, the present results show that the effects of lifting technique on low back loading depend on the task context and suggest that training in lifting technique cannot be based on only one technique advisable under all circumstances.

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