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Review paper

Stoop or squat: a review of biomechanical studies on lifting technique

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Abstract

Objective. To assess the biomechanical evidence in support of advocating the squat lifting technique as an administrative control to prevent low back pain.

Background. Instruction with respect to lifting technique is commonly employed to prevent low back pain. The squat technique is the most widely advised lifting technique. Intervention studies failed to show health effects of this approach and consequently the rationale behind the advised lifting techniques has been questioned.

Methods. Biomechanical studies comparing the stoop and squat technique were systematically reviewed. The dependent variables used in these studies and the methods by which these were measured or estimated were ranked for validity as indicators of low back load.

Results. Spinal compression as indicated by intra-discal pressure and spinal shrinkage appeared not significantly different between both lifting techniques. Net moments and compression forces based on model estimates were found to be equal or somewhat higher in squat than in stoop lifting. Only when the load could be lifted from a position in between the feet did squat lifting cause lower net moments, although the studies reporting this finding had a marginal validity. Shear force and bending moments acting on the spine appeared lower in squat lifting. Net moments and compression forces during lifting reach magnitudes, that can probably cause injury, whereas shear forces and bending moments remained below injury threshold in both techniques.

Conclusion. The biomechanical literature does not provide support for advocating the squat technique as a means of preventing low back pain.

Relevance

Training in lifting technique is widely used in primary and secondary prevention of low back pain, though health effects have not been proven. The present review assesses the biomechanical evidence supporting the most widely advocated lifting technique.

Keywords: Lifting; Prevention; Low back pain; Spine; Review; Administrative controls; Training and instruction

1. Introduction

In view of the high costs associated with low back pain (LBP) and the high recurrence rate of the complaints, primary prevention has received considerable interest. Several recent review studies on the epidemiology of LBP conclude that lifting is the best documented risk factor for this disorder [1–4]. In line with this, preventive strategies often involve measures aimed at reducing back load associated with lifting tasks. Next to engineering controls, administrative controls such as training and instruction in particular with respect to lifting technique are widely used [5–11]. Intervention studies have failed to demonstrate convincing effects of training and instruction with respect to lifting technique on musculoskeletal health. Health effects of training programmes with respect to lifting technique were either lacking or minimal [5,8,12–17]. This may be due to a lack of skill or willingness of workers to apply the lifting techniques taught [5,9,10,18], but also the rationale behind the principles taught has been questioned [9].

The most commonly advised lifting technique is the so-called squat technique or leg lift, in which the back remains as erect as possible and in which the knees are flexed [19]. It can easily be understood that compliance with this advise is often low, given the high energetic

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cost of this technique [20–22], causing higher perceived exertion and more rapid fatigue development [23,24], as compared to its exact opposite the stoop technique. In repetitive lifting experiments, subjects have been shown to shift from a squat technique to a stoop technique, probably to avoid or diminish fatigue development [25–28]. Better training programmes can possibly overcome this low compliance. However, if the rationale behind promoting the squat technique is dubious, more effort in improving methods of training and instruction does not seem warranted. The aim of the present review therefore was to evaluate the evidence that the lifting technique is an important determinant of the probability of contracting LBP. Since the premise behind training in lifting technique is that the mechanical load during lifting determines this probability, biomechanical studies on lifting technique were reviewed. This review was limited to studies comparing the stoop and squat techniques, as these are well defined and frequently studied techniques in manual materials handling. In addition, a limitation is made to symmetric lifting, since all the available data suggests that symmetric lifting is to be preferred over asymmetric lifting [29–35].

2. Methods

2.1. Literature search

This review was based on a literature search in the following databases: Medline, Current Contents, Embase, and NIOSHTIC, using the keywords lifting and technique. These references were screened on the basis of titles and abstracts and those papers concerning a biomechanical evaluation of lifting techniques were selected for further study. The literature retrieved in this way was supplemented with references from reviews with a somewhat broader scope [36–38] and studies cited in the previously retrieved papers.

2.2. Selection and evaluation of validity of dependent variables

It is unknown what structures are responsible for LBP, and it seems likely that different structures may be involved in different cases. Therefore, all mechanical loads likely to induce injury to structures in the low back will be considered, this includes loads on spinal structures (e.g., ligaments, intervertebral disc, vertebrae) and musculotendinous structures (e.g., muscle, musculotendinous junction, tendinous insertion).

The mechanical load on the osteoligamentous spine during symmetric lifting consist of three components, each of which according to in vitro studies has the potential to cause injury. High compression forces are caused mainly through back muscle activity. These may cause the vertebral endplate to fracture and the intervertebral disc to prolapse into the vertebra [39,40]. Considerable forward shear forces can occur, as a result of gravity acting on the upper body and of muscular forces. These shear forces can cause damage to the neural arch [41,42] and possibly to the facet joints. Finally, bending of the trunk imposes tensile stresses on the posterior spinal ligaments and the posterior intervertebral disc, which can cause damage to these structures [43,44]. Muscular damage is most likely to occur when high forces are sustained or produced repeatedly. Eccentric contractions are especially likely to cause muscular damage, but this type of damage appears to be reversible within days [45,46] and is somewhat outside the scope of this review. In conclusion, four parameters appear of interest: compression and shear acting on the spine, tensile stresses in the posterior spine, and muscle force. Note that these parameters are not independent. For example, the compression forces on the lumbar spine are determined mainly by muscle forces.

Unfortunately, none of the four variables of interest can be measured directly. Therefore, indicators of these parameters of back load have been used, some based on measurements, some on model calculations (summarised in Table 1). The validity of these indicators will be evaluated in the following and a score for validity of each indicator and estimation method will be given. This score will be used in weighing the results of different studies. Invalid indicators will be given a score 0 and will be excluded from the review. Measured and highly valid indicators of back load will get a score of 3, model-based sufficiently validated estimates will get a score of 2 and indicators with a limited validity will get a score of 1. Findings based on the latter category will be considered valid, only in case the results converge with evidence based on more valid indicators.

In general, measurements are to be preferred over model calculations in view of the assumptions involved in modelling. However, the possibilities for measurements of the load on the low back are, as stated above, very limited. The measurements that have been applied in studying lifting techniques are intra-discal pressure (IDP), intra-abdominal pressure (IAP), spinal shrinkage, and EMG.

IDP measurements can be considered the most direct indicator of compression forces acting on the spine [47,48]. These measurements are generally considered highly valid indicators of spinal compression, but the invasive nature limits their applicability. Consequently, only few data are available.

IAP has been suggested to be an indicator of spinal compression [49]. However, IAP increase has also been suggested to be a means of relieving the spine from high compression forces [50,51]. In addition to this inconsistency, the relationship between IAP and IDP appears to be disturbed by trunk posture [52–54]. Therefore,

Table 1
Parameters of back load and their indicators derived from direct measurements or model calculations evaluated for use in comparative studies of lifting technique

Parameter of back load	Indicator	Method	Evaluation [a]	Comments
Measured indicators				
Muscle force	EMG	Surface EMG	0	Low validity
Compression	IDP	Invasive, pressure transducer	3	
	IAP	Radio-pill catheter	0	Inconsistent theory, low validity
	Shrinkage	Stadiometry	1	Low repeatability
Shear	None			
Bending moment + ligament stress	None			
Model based estimates				
Muscle force	Net moment	Static LSM	1	
		Dynamic LSM	2	
	Estimated extensor moment	Surface EMG, kinematics, muscle length and shortening velocity correction	2	
Compression + shear	Estimated compression + estimated shear	Net moment, surface EMG	2	Depends on anatomical fidelity
		Net moment, optimisation	2	Depends on anatomical fidelity
		Net moment, SEM (constant moment arm)	0 [b]	Little information additional to net moment
Bending moment + ligament stress	Estimated ligament stress, estimated bending moment	Cadaver data, trunk kinematics, force-deformation relationship	2	

[a] 0 = Will be discarded, 1 = will be used in case of converging evidence, 2 = sufficiently valid for comparative use, 3 = valid indicator of back load.
[b] Used only if net moments not reported, ranking in these cases according to validity of estimate of net moment.

data on IAP will not be accepted as an indicator of back load in this review.

Spinal shrinkage measurements are also considered to be indicators of compressive back loading. If applied in a repeated measures design and given certain methodological criteria, such as exclusion of the influence of prior loading, spinal shrinkage appears to be a valid indicator of spinal compression for use in comparative studies [55]. However, the repeatability of spinal shrinkage measurements is low [55,56]. Therefore, an absence of effects of lifting technique might be due to a lack of statistical power. Converging evidence from several studies will be needed to draw conclusions with sufficient confidence.

Surface EMG measurements on the back muscles have been used as indicators of back muscle force in a range of studies. Whereas the EMG amplitude appears to be a valid indicator of muscle activation, it is not necessarily a valid indicator of back muscle force [57–59]. Only when combined in a model using information on muscle length and shortening velocity relating the EMG data to calibration data on an individual level can valid estimates of back muscle force in dynamic lifting tasks be attained. Therefore, the use of EMG will be dealt with below in discussing EMG based models of low back load.

Model based indicators of low back load include net moments, estimated muscle forces or muscle moments, estimated compression and shear forces and predicted bending moments resisted by the osteoligamentous spine or tensile forces in individual ligaments.

Neglecting passive tissue contributions, the peak net moment in a lifting task reflects the peak back muscle force minimally (i.e., neglecting antagonistic coactivation) required and as such also the major component of the compression force acting on the spine [60]. Actual muscle forces and compression forces are not completely determined by the net moment though, since the distribution of the net moment across muscles and levels of cocontraction may vary. Net moments can be calculated reliably through a linked segment model (LSM) [61,62]. Some LSMs neglect accelerations of body segments, which can produce substantial errors [63–65]. Since this review deals with a comparative analysis, the results of such static models will not be discarded. However, since systematic differences in the dynamic component of the moment about the lumbar spine might exist between the squat and stoop technique, static estimates of the differences in net moments will be considered sufficient evidence only in the case of convergence with dynamic estimates. In addition, the net moment can be estimated using EMG data and a model incorporating kinematic

Table 2
Overview of particulars and main results of the included studies[a]

Study	Nr.	Dependent variable	Method	Validity	Subjects	Load	Horizontal position	Stoop	Squat	Diff. % stoop	*p*-Value	Conclusion	Comments
Andersson et al. (1976)	52	IDP (Mpa)	Direct	3	3 f, 1 m	40	Fixed in front of feet				NS	=	Static pull
		IDP (Mpa)	Direct	3	3 f, 1 m	10	?	1.83	1.5	18	NS	=	Dynamic lift
Dieën et al. (1994)	74	Spinal shrinkage (mm)	Direct	1	11 m	8	25 vs. 30	3.9	4		NS	=	Horizontal position freely choosen
Rabinowitz et al. (1998)	75	Spinal shrinkage (mm)	Direct	1	10 m	20% bm	Fixed in front of feet	4.12	4.81		NS	=	
Park & Chaffin (1974)	76	Net moment (Nm)	Static LSM	1	–	0–16	37.5	81	8.8	–9	–	–	Model study
		Net moment (Nm)	Static LSM	1	–	0–16	50	100	111	–11	–	––	
		Net moment (Nm)	Static LSM	1	–	0–8	75	105	103	2	–	=	
Garg & Herrin (1979)	20	Net moment (Nm)	Static LSM	1	–	0–70	31 vs. 12	256	226	12	–	++	Model study
		Net moment (Nm)	Static LSM	1	–	0–50	38	238	246	–3	–	=	
Ekholm et al. (1982)	77	Net moment (Nm)	Static LSM	1	14 m, 1 f	12.8	Variable, close	217	160	26	<0.001	++	
		Net moment (Nm)	Static LSM	1	14 m, 1 f	12.8	Variable, far	217	200	8	NS	=	
Wax et al. (1987)	78	Net moment (Nm)	Static LSM	1	5 m	25	Variable	182	120	34	<0.0.01	++	Load between feet in squat
Lindbeck & Arborelius (1991)	79	Net moment (Nm)	Static LSM	1	10 m	12.8	30	186	167	10	<0.01	++	
Mittal & Malik (1991)	80	Net moment (Nm)	Static LSM	1	100 f	18 vs. 17	Variable	295	250	15	<0.05	++	Loads differed between techniques, static holding
Looze et al. (1992)	64	Net moment (Nm)	Static LSM	1	5 m	11	40[b]	184	185	–1	NS	=	
Bush-Joseph et al. (1988)	81	Net moment (Nm)	Dynamic LSM	2	10 m	15	38			–18	<0.05	––	
Buseck et al. (1988)	82	Net moment (Nm)	Dynamic LSM	2	10 m	5–25	37	309	268	13	?	?	Stoop = free technique, performed faster

(*continued overleaf*)

Table 2 (*continued*)

Study	Nr.	Dependent variable	Method	Validity	Subjects	Load	Horizontal position	Stoop	Squat	Diff. % stoop	*p*-Value	Conclusion	Comments
Potvin et al. (1991)	83	Net moment (Nm)	Dynamic LSM	2	15 m	6–32	?	290	277	4	?	?	
Lindbeck & Arborelius (1991)	79	Net moment (Nm)	Dynamic LSM	2	10 m	13	30	268	290	−8	NS	=	
Looze et al. (1992)	64	Net moment (Nm)	Dynamic LSM	2	5 m	11	40^{b}	265	255	4	NS	=	
Toussaint et al. (1992)	85	Net moment (Nm)	Dynamic LSM	2	8 m	15	Fixed in front of feet	225^{b}	225^{b}	0	NS	=	
Hagen & Harms-Ringdahl (1994)	86	Net moment (Nm)	Semi-dynamic LSM	2	10 m	1–17	Fixed in front of feet	200^{b}	193^{b}	0	NS	=	
Dolan et al. (1994a)	87	Extensor moment (Nm)	EMG based	2	23 m, 126 f	10	?	243	252	−4	<0.05	–	
Dolan et al. (1994b)	88	Extensor moment (Nm)	EMG based	2	21 m, 18 f	0–30	?	228	254	−11	<0.0001	– –	
Dieën et al. (1994)	74	Net moment (Nm)	Dynamic LSM	2	11 m	8	25 vs. 30	196	214	−9	0.04	–	Horizontal position freely choosen
Toussaint et al. (1997)	89	Net moment (Nm)	Dynamic LSM	2	8 m	20% BM	51.5^{b}	368	366	1	NS	=	
Kjellberg et al (1998)	94	Net moment (Nm)	Dynamic LSM	2	12 f	8.7	50^{b}	150	151	−1	NS	=	
Looze et al. (1998)	90	Net moment (Nm)	Dynamic LSM	2	8 m	7–16	38^{b}	210	228	−9	<0.001	– –	
Troup et al. (1983)	91	Compression (N)	Dynamic LSM + SEM	2	10 m	15	In front of feet	5767	6039	−5	<0.001	–	Feet placed asymmetrically in squat
Leskinen et al. (1983)	92	Compression (N)	Dynamic LSM + SEM	2	20 m	15	Fixed feet under load	6365	5866	8	<0.01	+	
Leskinen et al. (1985)	63	Compression (N)	Static LSM + SEM	1	20 m	15	Fixed feet under load	3989	4033	−1	NS	?	
Anderson & Chaffin (1986)	73	Compression (N)	Static LSM + opt.	1	1	5–40	Between legs	5055	3304^{c}	35	–	++	Crude anatomical model
		Compression (N)	Static LSM + opt.	1	1	5–40	In front of feet	3931	4275^{c}	−9	–	–	Partly predicted kinematics
Potvin et al. (1991)	83	Compression (N)	Dynamic LSG + EMG	2	15 m	15	?	4275	4724	−11	< 0.05	– –	
Potvin et al. (1992)	84	Compression (N)	Dynamic LSM + EMG	2	13 m	6–32	34 vs. 32			−6^{b}	0.02	–	

(*continued on next page*)

Table 2 (*continued*)

Study	Nr.	Dependent variable	Method	Validity	Subjects	Load	Horizontal position	Stoop	Squat	Diff. % stoop	*p*-Value	Conclusion	Comments
Chaffin & Page (1994)	93	Mass at 3400N comp. (Kg)	Static LSM + opt.	1	–	Dep. var.	38-58	16 ^{b}	10 ^{b}		–	– –	Model study, predicted kinematics
Potvin et al. (1991)	83	Shear (N)	Dynamic LSM + EMG	2	15 m	15	?	450	156	65	<0.05	++	
Anderson & Chaffin (1986)	73	Fascial strain (%)	Kinematics based	2	1	5–40	Between legs	3.6	2.3 ^{c}	36	–	++	Partly predicted kinematics
		Fascial strain (%)	Kinematics based	2	1	5–40	In front of feet	8.8	2.4 ^{c}	73	–	++	Partly predicted kinematics
Dolan et al. (1994a)	87	Bending moment (Nm)	Kinematics based	2	23 m, 126 f	10	?	75	54	28	<0.05	++	
Dolan et al. (1994b)	88	Bending moment (% max)	Kinematics based	2	21 m, 18 f	0–30	?	31	18	42	<0.05	++	

[a] m – male; f – female; – – – substantial (>10%) negative effect of squat technique; – is limited (<10%) negative effect of squat technique; = – no effect of lifting technique; + – limited (<10%) positive effect of squat technique; ++ – substantial (>10%) positive effect of squat technique.

[b] Estimated.

[c] Curved back squat and flat back squat averaged.

data [66]. Comparisons to the outcomes of LSMs indicate this to be a valid method [67,68].

Muscle forces can be estimated from the net moment using optimisation, EMG, or using a single-equivalent muscle model (SEM). The latter adds little to the information contained in the net moment and will be discarded. The former techniques have been used in studying lifting techniques but only with the aim of predicting forces acting on the spine. Estimated muscle forces were not compared between the two techniques.

Using net moments as a starting point, forces acting on the spine can be calculated using a model of the trunk musculature. It has been shown that these estimates heavily depend on the anatomical fidelity of the model [69–71]. Major factors in this respect are the changes with trunk flexion of the moment arms of the muscles [72] and of the orientation of the muscles with respect to the spine [71]. These factors have been neglected in all SEMs applied to date. The results from such models will therefore be discarded, but the net moments from these studies when reported or when these can be calculated from the data provided will be included in the review. If the net moments cannot be derived from these papers, the reported compression forces will be considered along with the results from papers reporting net moments, since compression forces estimated with a SEM are strongly determined by the net moment. The studies using more sophisticated models to estimate compression forces apply either EMG or optimisation to obtain muscle force and finally the forces on the spine. Both methods involve a number of assumptions, which have not been sufficiently validated. A ranking of the validity of the two approaches can therefore not be made. The anatomical fidelity of the models applied will be qualitatively evaluated.

Spinal bending moments or ligament and disc stresses are estimated from trunk kinematics using models based on cadaver data. This involves a generalisation of the force-deformation relationships of the structures studied in vitro to the in vivo situation. In a comparative analysis this does not seem to be a major problem. However, the assumed deterministic relationship between trunk kinematics measured externally and internal kinematics of the spine may limit the validity.

3. Results

In total 27 studies comparing stoop and squat lifting with respect to the mechanical load on the back were included in this review [20,52,63,64,73–94], some reported on several dependent biomechanical variables. The main particulars and findings of these studies have been listed in Table 2. In the majority model-based dependent variables, in particular the net moment, were used. In only four studies measured indicators were used, of which in one study IAP was used exclusively [91]. In three studies the compression force was estimated on the basis of a SEM, while the net moments were not reported. The results of these studies will be considered along with those studies reporting net moments. Only four studies reported estimates of compression force based on more sophisticated models and only one reported shear forces. Finally, three studies considered ligament stresses or spinal bending moments.

In several studies the comparison of the techniques was confounded with other variables. The horizontal distance often varied with technique, but this can be considered part and parcel of the technique. In one study the mass lifted varied with technique [80]. However, since the effect of lifting technique was a 15% change in the estimated net moment and the load mass differed by only 5%, the conclusions of this study appear to hold at least qualitatively. In some studies the velocity of lifting was reported to be higher in squat lifting as compared to stoop lifting [74,82]. Since net moments increase with lifting velocity [64,81,82], this may confound the comparison of techniques. This may have occurred in more studies, since velocity was usually not strictly controlled. However, since this occurred even when subjects were instructed to lift at a fixed pace [74], this can again be considered an integral part of the lifting technique. Therefore, no studies were excluded because of confounding of lifting technique with velocity of lifting. One study reported an opposite effect of technique on velocity, but in this study the squat technique was actually compared to a freely chosen technique [81].

The three studies in which sufficiently valid measured indicators of back load were used have been listed in the top rows of Table 2. IDP was measured in just one study involving only four subjects. No significant effect of lifting technique was found. The two studies employing spinal shrinkage measurements also failed to show any difference between stoop and squat lifting. In conclusion, measured indicators of low back load do not provide evidence, supporting preference of one lifting technique to the other. It must be kept in mind that a lack of statistical power may underlie these findings.

The seven studies using a static LSM to estimate the net moment yielded varying results. The majority of studies ($n = 5$) predicted a substantial reduction (10–34%) in back load when using the squat technique in at least one of the experimental conditions. This may, however, be explained by differences in the horizontal position of the load. This issue was specifically addressed in two of these studies [20,77], which showed that when horizontal distance is constant the effect of technique disappears. The large positive effects associated with squat lifting in some of these studies can, in line with this, be explained by the fact that the load is lifted from a position between the feet. The thirteen studies in which the net moment or extensor moment was estimated using dynamic analysis techniques found back loads in the two techniques to be either significantly higher (4–18%) in squat lifting or not significantly different. In ten of these studies, the loads were lifted from a position in front of the feet. In three studies the horizontal position of the load was not described, nor could it be derived from any of the figures. Two studies did not report whether the differences found were significant. One of these did report a substantially lower (13%) net moment in squat lifting. However, in this study subjects were not instructed with respect to the stoop technique and so actually used a free technique, which is usually intermediate between squat and stoop lifting [95]. In addition they performed this technique at a substantially higher velocity, which will strongly increase the net moment [64,81,82]. The three studies providing compression force estimates based on a SEM did yield disparate results. Leskinen analysed the same data in two papers, dynamically and statically [63,92]. The dynamic analysis yielded significantly lower compression estimates for squat lifting. In the static analysis no significant difference was found. Troup et al. [91], using the same model, found higher compression estimates for squat lifting. Again differences in load placement may explain these discrepancies. In the study by Leskinen et al. [92] subjects placed the feet below the load. As outlined in the methods section, these studies cannot actually be considered to yield a valid prediction of compression forces, but the calculation of net moments to which the compression estimates are strongly related does appear to be valid. These results will therefore be pooled with the results on net moments and extensor moments. Concluding on this complete category, the data suggest that squat lifting may be advantageous for a limited range of lifting tasks in which the load can be lifted from between the feet (up to 34% reduction in net moment). In situations where this not the case, the effect of squat lifting appears to be negative rather than positive though this effect is smaller (up to 11% increase in net moment).

In one of the studies reporting more sophisticated estimates of compression forces [73] a still fairly crude anatomical model of the lumbar spinal musculature was used [96]. Furthermore, this and one other study [93] were based on completely or partially predicted kinematics instead of experimental data and the LSM used to estimate the net moments was static. Potvin et al. [83,84] used a detailed anatomical model [97] and the net moments were calculated employing a dynamic LSM and empirical kinematic data. Overall, the results from these four studies appear in line with the above conclusions drawn on the basis of moment estimates. Given the strong relation between net moments and compression forces [84], this correspondence is not surprising.

Results on shear forces were reported in one study only [83]. As expected, shear forces were higher in stoop lifting than in squat lifting. Bending moments (and ligament stresses) were found to be substantially higher in stoop lifting than in squat lifting in all three studies reporting this variable [73,87,88].

4. Discussion

The main findings of this review were a potential positive effect of squat lifting in terms of net moments and compression forces on the spine in a limited range of lifting tasks, and no or even a limited negative effect in other lifting tasks. In terms of shear forces on the spine and tensile stresses in the posterior spinal ligaments the squat lift was found to be beneficial.

Positive effects of squat lifting with respect to estimated moments and compression forces were found only when squat lifting allowed for lifting from a position between the feet. This effect appears to entail a maximum reduction in back load by about one third. In practice, lifting from a position between the feet is often not possible and these results thus appear to be valid for a limited range of tasks. Actually in a study by Dieën et al. [74], subjects lifting a barbell preferred a larger horizontal distance when using a squat technique as compared to a stoop technique. In addition, data on lifting with the squat technique from a position between the feet based on a dynamic analysis appears to be missing. Actually the studies showing this benefit of squat lifting had a rating of 1 for the method used. Hence the validity of the positive findings on squat lifting in these cases may be questioned. A striking finding in this respect is the fact that the positive effect of squat lifting in the study by Lindbeck and Arborelius [79] disappeared, when reanalysing the same data using a dynamic LSM. The much higher ground reaction forces in squat lifting related to the greater vertical excursion of the body centre of mass [89], which are ignored in a static analysis, may account for this. However, in comparable studies this effect was not found, or the dynamic analysis predicted, in contrast to the static analysis, a positive effect of the squat technique [63,64]. Hence the results from the static analyses should not be discarded altogether.

In lifting tasks where the load is not lifted from a position between the feet, the net moment and compression tended to be lower using the stoop technique. In contrast, in all studies reporting shear and bending moments, these were higher in stoop lifting. Consequently, the parameters of back load these indicators stand for need to be weighted with respect to each other. When a parameter increases with a change in lifting technique, but remains well below injury threshold, this increase can be considered of little importance. Thus the injury potential of the parameters of back load could be used to obtain such a weighting.

The net moments in Table 2, which, as determined using a dynamic LSM, range from about 190 to 370 Nm for male subjects, can be compared to the muscle strength, as determined in static strength tests. In several experiments we found the average maximum extension moment in healthy males to be over 300 Nm with a standard deviation of up to 30% of the mean [98–101]. Therefore, even in the healthy young male (age < 30 yr) population included in these experiments the net moments in lifting can approach the static maximum moment. In a selected group of five physically inactive young males the average maximum moment was 269 (SD 35) Nm [99], comparable to the average value of 234 Nm among 27 male industrial workers not selected for age [102]. McNeil et al. [103] reported even lower values. For inactive subjects or subjects over 30 years old, net moments during lifting can thus certainly exceed the voluntary static maximum moment. The incidence of back injuries appears to increase when this occurs in occupational lifting tasks [104,105]. In view of these findings, the effect of lifting technique on the net moment can be considered important.

Lumbar spinal motion segments fail under compression at levels in between about 2 and 10 kN [40,106,107]. Their strength appears to be age and sex dependent. Compression forces of 3–5 kN, as occur during lifting according to the studies listed in Table 2, are high enough to cause failure in females over 20 and in males over 40 years old [106] and probably in younger males under repetitive loading [108,109]. It has been hypothesised that a major proportion of all LBP cases is attributable to excessive compression during tasks such as lifting [110]. Consequently, effects of lifting technique on compression forces can be considered important. In the context of the comparison of stoop and squat lifting, it is important to note that compression strength is not significantly affected by flexion of the motion segment [111].

Shear forces on lumbar spinal motion segments were reported in one study only. Forward shear forces of up to 450 N were found. To our knowledge only two studies present strength data of human motion segments with respect to anterior shear. Cyron et al. [42], reported strength values ranging from a minimum of about 1 to a maximum of 2.5 kN. Lamy and associates [41] reported a similar minimum strength and a maximum strength of over 5 kN. This would suggest that shear forces during lifting do not pose a serious injury risk as was suggested by Cyron [42]. However, it should be kept in mind that in repetitive loading lower shear forces may cause damage [112]. In addition, shear forces estimates during lifting are strongly dependent on the functional and anatomical assumptions in the model used [71,113]. In conclusion, though the relevance of loading in anterior shear during lifting has not been shown convincingly, reductions in shear force may prove important, when more accurate data on shear magnitude during lifting as well as on the shear strength of the spine become available.

The bending moments carried by the osteoligamentous spine during lifting can directly be compared to the maximum bending moments as was actually done in one of the studies in Table 2 [88]. This study, as well as a previous study [114], showed that bending moments during lifting remain well below the injury threshold. Consequently, the difference in bending moment between the two lifting techniques can be considered not very relevant.

In conclusion, the present review shows that there is no substantial biomechanical evidence to support training and instruction in which the squat technique is advocated. Evidence obtained with other approaches such as psychophysics and exercise physiology, generally appears to support this conclusion [20–24]. In addition, it has been shown that balance loss during lifting, which may cause excessive back load, is more likely to occur when using the squat technique as compared to the stoop technique [89]. It is, therefore, suggested that controls for preventing LBP associated with lifting should be focussed on other aspects of lifting. The most promising interventions would deal with those factors, that have been shown to substantially affect the mechanical load on the low back, such as asymmetry [29,31–33,35], speed [64,81,82], horizontal and vertical position of the load [115,116], and load mass.

References

[1] Ferguson SA, Marras WS. A literature review of low back disorder surveillance measures and risk factors. Clinical Biomechanics 1997;12(4):211–26.

[2] Burdorf A, Sorock G. Positive and negative evidence of risk factors for back disorders. Scandinavian Journal of Work, Environment and Health 1997;23:243–56.

[3] Kuiper J, Burdorf A, Verbeek JHAM, Frings-Dresen MHW, Beek AJvd, Viikari-Juntura ERA. Epidemiologic evidence on manual materials handling as a risk factor for back disorders: A systematic review. International Journal of Industrial Ergonomics, in press.

[4] Frank JW, Kerr MS, Brooker AS, DeMaio SE, Maetzel A, Shannon HS, et al. Disability resulting from low back pain. Part I: What do we know about primary prevention? A review of the scientific evidence on prevention before disability begins. Spine 1996;21(24):2908–917.

[5] Videman T, Rauhala H, Asp S, Lindstrom K, Cedercreutz G, Kamppi M, et al. Patient-handling skill back injuries and back pain: An intervention study in nursing. Spine 1989;14:148–56.

[6] Nygård CH, Merisalo T, Arola H, Manka ML, Huhtala H. Effects of work changes and training in lifting technique on physical strain- a pilot study among female workers of different ages. International Journal of Industrial Ergonomics 1998;21(1):91–8.

[7] Schenk RJ, Doran RL, Stachura JJ. Learning effects of a back education program. Spine 1996;21(19):2183–8.

[8] Lagerstrom M, Josephson M, Pingel B, Tjernstrom G, Hagberg M. Evaluation of the implementation of an education and training programme for nursing personnel at a hospital in Sweden. International Journal of Industrial Ergonomics 1998;21(1):79–90.

[9] St-Vincent M, Tellier C, Lortie M. Training in handling: an evaluative study. Ergonomics 1989;32(2):191–210.

[10] Nevalapuranen N. Effects of occupationally-oriented rehabilitation on farmers work techniques musculoskeletal symptoms, and work ability. Journal of Occupational Rehabilitation 1996;6(3):191–200.

[11] Chavalinitikul C, Nopteepkangwan N, Kanjanopas F. Improvement of lifting heavy objects work. Journal of Human Ergology 1995;24:55–8.

[12] Brown JR. Factors contributing to the development of low back pain in industrial workers. American Industrial Hygienic Association Journal 1975;36:26–31.

[13] Dehlin O, Hedenrud B, Horal J. Back symptoms in nursing aides in a geriatric hospital. Scandinavian Journal of Rehabilitation Medicine 1976;8:47–53.

[14] Dehlin O, Berg S, Andersson GBJ. Effect of physical training and ergonomic counselling on the psychological perception of work and on the subjective assessment of low-back insufficiency. Scandinavian Journal of Rehabilitation Medicine 1981;13:1–9.

[15] Snook SH, Campanelli RA, Hart JW. A study of three preventive approaches to low back injury. Journal of Occupational Medicine 1978;20:478–81.

[16] Stubbs DA, Buckle PW, Hudson MP, Rivers PM. Back pain in the nursing profession. II. The effectiveness of training. Ergonomics 1983;26(8):767–79.

[17] Harber P, Pena L, Billet E, Greer D, Kim K. Personal history, training and worksite as predictors of back pain in nurses. American Journal of Industrial Medicine 1994;25:519–26.

[18] Chaffin DB, Gallay LS, Woolley CB, Kuciemba SR. An evaluation of the effect of a training program on worker lifting postures. International Journal of Industrial Ergonomics 1986;1:127–36.

[19] Garg A, Moore JS. Prevention strategies and the low back in industry. Occupational Medicine 1992;7(4):629–40.

[20] Garg A, Herrin GD. Stoop or squat, a biomechanical and metabolical evaluation. A. I. I. E. Transactions 1979;11:293–302.

[21] Welbergen E, Kemper HCG, Knibbe JJ, Toussaint HM, Clijssen L. Efficiency and effectiveness of stoop and squat lifting at different techniques. Ergonomics 1991;34:613–24.

[22] Duplessis DH, Greenway EH, Keene KL, Lee IE, Clayton RL, Metzler T, et al. Effect of semi-rigid lumbosacral orthosis use on oxygen consumption during repetitive stoop and squat lifting. Ergonomics 1998;41(6):790–97.

[23] Hagen KB, Hallen J, Harms-Ringdahl K. Physiological and subjective responses to maximal repetitive lifting employing stoop and squat technique. European Journal of Applied Physiology 1993;67:291–7.

[24] Kumar S. The physiological cost of three different methods of lifting in sagittal and lateral planes. Ergonomics 1984;27(4):425–33.

[25] Dieën JHv. Effects of repetitive lifting on the kinematics, inadequate anticipatory control or adaptive changes? Journal of Motor Behavior 1998;30(1):20–32.

[26] Resnick M. Postural changes due to fatigue. Computers & Industrial Engineering 1996;31(1-2):491–4.

[27] Fogleman M, Smith JL. The use of biomechanical measures in the investigation of changes in lifting strategies over extended periods. International Journal of Industrial Ergonomics 1995;16(1):57–71.

[28] Trafimow JH, Schipplein OD, Novak GJ, Andersson GBJ. The effects of quadriceps fatigue on the technique of lifting. Spine 1993;18(3):364–7.

[29] Kingma I, Dieën JHv, Looze MPd, Toussaint HM, Dolan P, Baken CTM. Asymmetric low back loading in asymmetric lifting

movements is not prevented by pelvic twist. Journal of Biomechanics 1998;31(6):527–34.

[30] Marras WS, Lavender SA, Leurgans SE, Fathallah FA, Ferguson SA, Allread WG, et al. Biomechanical risk factors for occupationally related low-back disorders. Ergonomics 1995;38(2):377–10.

[31] Marras WS, Davis KG. Spine loading during assymetric lifting using one versus two hands. Ergonomics 1998;41(6):817–34.

[32] Marras WS, Granata KP. A biomechanical assessment and model of axial twisting in the thoracolumbar spine. Spine 1995;20(21):1440–51.

[33] Marras WS, Granata KP. Spine loading during trunk lateral bending motions. Journal of Biomechanics 1997;30(7):697–703.

[34] Kelsey JL, Githens PB, White AA, Holford TR, Walter SD, O'Connor T, et al. An epidemiological study of lifting and twisting on the job and risk for acute prolapsed lumbar intervertebral disc. Journal of Orhopaedic Research 1984;2(1):61–6.

[35] Fathallah F, Marras WS, Parnianpour M. An assessment of complex spinal loads during dynamic lifting tasks. Spine 1998;23(6):706–16.

[36] Yu TS, Roht LH, Wise RA, Kilian DJ, Weir FW. Low-back pain in industry. An old problem revisited. Journal of Occupational Medicine 1984;26(7):517–24.

[37] Hsiang SM, Brogmus GE, Courtney TK. Low-back-pain (lbp) and lifting technique – a review. Int J Ind Ergonomics 1997;19(1):59–74.

[38] Kroemer KHE. Personnel training for safer manual handling. Ergonomics 1992;35(9):1119–34.

[39] Perey O. Fracture of the vertebral endplate in the human spine. Acta Orthopedica Scandinavica 1957;Suppl 25.

[40] Brinckmann P, Biggeman M, Hilweg D. Prediction of the compressive strength of human lumbar vertebrae. Clinical Biomechanics 1989;Suppl 12:1–27.

[41] Lamy C, Bazergui A, Kraus H, Farfan HF. The strength of the neural arch and the etiology of spondylolysis. Orthopaedic Clinics of North America 1975;6:215–31.

[42] Cyron BM, Hutton WC, Troup JDG. Spondylolytic fractures. Journal of Bone and Joint Surgery – British Volume 1976;58B:462–6.

[43] Adams MA, Hutton WC. Prolapsed intervertebral disc: a hyperflexion injury. Spine 1982;7:184–91.

[44] Adams MA, Green TP, Dolan P. The strength in anterior bending of lumbar intervertebral discs. Spine 1994;19(19):2197–203.

[45] Armstrong RB. Mechanism of exercise-induced delayed onset muscular soreness: a brief review. Medicine and Science in Sports and Exercise 1984;16(6):529–38.

[46] Stauber WT. Eccentric action of muscles: Physiology injury, and adaptation. Exercise and Sport Sciences Reviews 1989;17:157–85.

[47] Nachemson A. Lumbar intradiscal pressure. Acta Orthopaedica Scandinavica 1960;43:9.

[48] Nachemson A, Morris JM. In vivo measurements of intradiscal pressure. Journal of Bone and Joint Surgery 1964;46A:1077–92.

[49] Davis PR. The use of intra-abdominal pressure in evaluating stresses on the lumbar spine. Spine 1981;6:90–2.

[50] Bartelink DL. The role of abdominal pressure in relieving the pressure on the lumbar intervertebral disc. Journal of Bone and Joint Surgery 1957;39B:718–25.

[51] Morris JM, Lucas DB, Bresler B. Role of the trunk in stability of the spine. Journal of Bone and Joint Surgery 1961;43A:327–51.

[52] Andersson GBJ, Örtengren R, Nachemson A. Quantitative studies of back loads in lifting. Spine 1976;1:178–85.

[53] Schultz A, Andersson G, Örtengren R, Haderspeck K, Nachemson A. Loads on the lumbar spine. Validation of a biomechanical analysis by measurements of intradiscal pressure and myoelectric signals. Journal of Bone and Joint Surgery 1982;64A:713–20.

[54] Schultz GBJ, Nachemson AL. Andersson. Valsalva maneuver biomechanics Effects on lumbar trunk loads of elevated intraabdominal pressures. Spine 1986;11:476–9.

[55] Dieën JHv, Toussaint HM. Spinal shrinkage as a parameter of functional load of the human spine. Spine 1993;18:1504–14.

[56] McGill SM, Wijk MJv, Axler CT, Glelsu M. Studies of spinal shrinkage to evaluate low-back loading in the workplace. Ergonomics 1996;39(1):92–102.

[57] Mouton LJ, Hof AL, Jongh HJd, Eisma WH. Influence of posture on the relation between surface electromyogram amplitude and back muscle moment;consequences for the use of surface electromyogram to measure back load. Clinical Biomechanics 1991;6:245–51.

[58] Potvin JR, Norman RW, McGill SM. Mechanically corrected EMG for the continuous estimation of erector spinae muscle loading during repetitive lifting. European Journal of Applied Physiology 1996;74:119–32.

[59] Dieën JHv, Visser B. Estimating net lumbar moments from EMG data. The validity of calibration procedures. Journal of Electromyography and Kinesiology, in press.

[60] Dieën JHv, Kingma I. Total trunk muscle force and spinal compression are lower in asymmetric moments as compared to pure extension moments. Journal of Biomechanics, in press.

[61] Looze MPd, Bussmann JBJ, Kingma I, Toussaint HM. Validation of a dynamic linked segment model to calculate joint moments in lifting. Clinical Biomechanics 1992;7:161–9.

[62] Kingma I, Looze MPv, Toussaint HM, Klijnsma HG, Bruijnen TBM. Validation of a full body 3-D dynamic linked segment model. Human Movement Science 1996;15:833–860.

[63] Leskinen TPJ. Comparison of static and dynamic biomechanical models. Ergonomics 1985;28:285–91.

[64] Looze MPd, Kingma I, Thunnissen W, Wijk MJv, Toussaint HM. The evaluation of a practical biomechanical model estimating lumbar moments in occupational activities. Ergonomics 1994;37(9):1495–502.

[65] McGill SM, Norman RW. Dynamically and statically determined low back moments during lifting. Journal of Biomechanics 1985;18(12):877–85.

[66] Dolan P, Adams MA. The relationship between EMG activity and extensor moment generation in the erector spinae muscles during bending and lifting activities. Journal of Biomechanics 1993;26(4/5):513–22.

[67] Baten CTM, Oosterhoff P, Luinge H, Veltink PH, Dieën JHv, Dolan P. Quantitative assessment of mechanical low back load in the field: validation in asymmetric lifting. In: Seppälä P, Luoparjärvi T, Nygård C-H, Mattila M, editors. Proceedings of the 13th Triennial Congress of the International Ergonomics Association. Helsinki: Finnish Institute of Occupational Health; 1997:488–490.

[68] Dolan P, Adams MA, Kingma I, Looze MPd, Dieën JHv, Toussaint HM. High fluctuating muscle forces act on the lumbar spine during lifting. Journal of Bone and Joint Surgery – British Volume 1998;80B Suppl II:178.

[69] Nussbaum MA, Chaffin DB, Rechtien CJ. Muscle lines-of-action affect predicted forces in optimization-based spine muscle modeling. Journal of Biomechanics 1995;28(4):401–9.

[70] McGill SM, Norman RW. Effects of an anatomically detailed erector spinae model on l4/l5 disc compression and shear. Journal of Biomechanics 1987;20(6):591–600.

[71] Dieën JHv, Looze MPd. Sensitivity of single-equivalent trunk extensor muscle models to anatomical and functional assumptions. Journal of Biomechanics (32) 1999;2:195–8.

[72] Tveit P, Daggfeldt K, Hetland S, Thorstensson A. Erector spinae lever arm length variations with changes in spinal curvature. Spine 1994;19(2):199–204.

[73] Anderson CK, Chaffin DB. A biomechanical evaluation of five lifting techniques. Applied Ergonomics 1986;17:2–8.

[74] Dieën JHv, Creemers M, Draisma I, Toussaint HM. Repetitive lifting and spinal shrinkage, effects of age and lifting technique. Clinical Biomechanics 1994;9:367–74.

[75] Rabinowitz D, Bridger RS, Lambert MI. Lifting technique and abdominal belt usage: a biomechanical, physiological and subjective investigation. Safety Science 1998;28(3):155–64.

[76] Park KS, Chaffin DB. A biomechanical evaluation of two methods of manual load lifting. A.I.I.E. Transactions 1974;6:105–13.

[77] Ekholm J, Arborelius UP, Nemeth G. The load on the lumbosacral joint and trunk muscle activity during lifting. Ergonomics 1982;25(2):145–61.

[78] Wax C, Flenghi D, Meyer J. Comparison of two load lifting techniques. Biomechanical analysis and physiological costs. Travail Humain 1987;50(4):334–45.

[79] Lindbeck L, Arborelius UP. Inertial effects from single body segments in dynamic analysis of lifting. Ergonomics 1991;34:421–33.

[80] Mittal M, Malik SL. Biomechanical evaluation of lift postures in adult Koli female workers. Ergonomics 1991;34(1):103–8.

[81] Bush-Joseph C, Schipplein O, Andersson GBJ, Andriacchi TP. Influence of dynamic factors on the lumbar spine moment in lifting. Ergonomics 1988;31(2):211–6.

[82] Buseck M, Schipplein O, Andersson GBJ, Andriacchi TP. Influence of dynamic factors and external loads on the moment at the lumbar spine in lifting. Spine 1988;13:918–21.

[83] Potvin JR, McGill SM, Norman RW. Trunk muscle and lumbar ligament contributions to dynamic lifts with varying degrees of trunk flexion. Spine 1991;16:1099–107.

[84] Potvin JR, Norman RW, Eckenrath ME, McGill SM, Bennet GM. Regression models for the prediction of dynamic L4/L5 compression forces during lifting. Ergonomics 1992;35:187–201.

[85] Toussaint HM, Baar CEv, Langen PPv, Looze MPd, Dieën JH. Coordination of the leg muscles in backlift and leglift. Journal of Biomechanics 1992;25:1279–89.

[86] Hagen KB, Harmsringdahl K. Ratings of perceived thigh and back exertion in forest workers during repetitive lifting using squat and stoop techniques. Spine 1994;19(22):2511–7.

[87] Dolan P, Mannion AF, Adams MA. Passive tissues help the back muscles to generate extensor moments during lifting. Journal of Biomechanics 1994;27(8):1077–85.

[88] Dolan P, Earley M, Adams MA. Bending and compressive stresses acting on the lumbar spine during lifting activities. Journal of Biomechanics 1994;27(10):1237.

[89] Toussaint HM, Commissaris DACM, Beek PJ. Anticipatory postural adjustments in the back and leg lift. Medicine and Science in Sports and Exercise 1997;29(9):1216–24.

[90] Looze MPd, Dolan P, Kingma I, Baten CTM. Does an asymmetric straddle-legged lifting movement reduce the low-back load? Human Movement Science 1998;17:243–59.

[91] Troup JDG, Leskinen TPJ, Stålhammar HR, Kuorinka IAA. A comparison of intraabdominal pressure increases, hip torque, and lumbar intervertebral compression in different lifting techniques. Human Factors 1983;25(5):517–25.

[92] Leskinen TPJ, Stalhammar HR, Kuorinka IAA, Troup JGD. A dynamic analysis of spinal compression with different lifting techniques. Ergonomics 1983;26(6):595–604.

[93] Chaffin DB, Page GB. Postural effects on biomechanical and psychophysical weight-lifting limits. Ergonomics 1994;37(4): 663–76.

[94] Kjellberg K, Lindbeck L, Hagberg M. Method and performance: two elements of work technique. Ergonomics 1988;41(6):798–816.

[95] Burgess-Limerick R, Abernethy B. Effect of load distance on self-selected manual lifting technique. International Journal of Industrial Ergonomics 1998;22(4-5):367–72.

[96] Anderson CK, Chaffin DB, Herrin CD, Mathews LS. A biomechanical model of the lumbosacral joint during lifting activities. Journal of Biomechanics 1985;18:571–84.

[97] McGill SM, Norman RW. Partitioning of the L4-L5 dynamic moment into disc, ligamentous, and muscular components during lifting. Spine 1986;7:666–78.

[98] Dieën JHv. Asymmetry of erector spinae muscle-activity in twisted postures and consistency of muscle activation patterns across subjects. Spine 1996;21(22):2651–61.

[99] Dieën JHv, Heijblom P. Reproducibility of isometric trunk extension torque, trunk extensor endurance, and related electromyographic parameters in the context of their clinical applicability. Journal of Orthopaedic Research 1996;14:139–43.

[100] Dieën JHv, Böke B, Oosterhuis W, Toussaint HM. The influence of torque and velocity on erector spinae muscle fatigue and its relationship to changes of electromyogram spectrum density. European Journal of Applied Physiology 1996;72:310–5.

[101] Dieën JHv, Oude Vrielink HHE, Housheer FAF, Lötters FJB, Toussaint HM. Trunk extensor endurance and its relationship to electromyogram parameters. European Journal of Applied Physiology 1993;66:388–96.

[102] Chaffin DB, Andersson GBJ. Occupational biomechanics. 2nd ed. New York: Wiley, 1991.

[103] McNeill T, Warwick D, Andersson G. Trunk strengths in attempted flexion, extension, and lateral bending in healthy subjects and patients with low-back disorders. Spine 1980;5:529–38.

[104] Herrin GD, Jaraiedi M, Anderson CK. Prediction of overexertion injuries using biomechanical and psychophysical models. American Industrial Hygiene Association Journal 1986;47:322–30.

[105] Chaffin DB, Park KS. A longitudinal study of low back pain as associated with occupational weight lifting factors. American Industrial Hygiene Association Journal 1973;34:513–25.

[106] Jäger M, Luttmann A. Assessment of low-back load during manual materials handling. In: Seppälä P, Luopajärvi T, Nygård CH, Mattila M, editors. 13th Triennial Congress of the International Ergonomics Association 1997. Tampere: Finnish Institute of Occupational Health. 1997:171–173.

[107] Ørtoft G, Mosekilde L, Hasling C, Mosekilde L. Estimation of vertebral body strength by dual photon absorptiometry in elderly individuals: Comparison between measurements of total and vertebral body mineral. Bone 1993;14:667–73.

[108] Spengler DM, Hansson TH, Keller TS. Mechanical behaviour of the human lumbar spine II Fatigue strength during dynamic compressive loading. Journal of Orthopaedic Research 1987;5:479–87.

[109] Brinckmann P, Biggeman M, Hilweg D. Fatigue fracture of human lumbar vertebrae. Clinical Biomechanics 1988;Suppl 1: 1–27.

[110] Dieën JHv, Weinans H, Toussaint HM. Fractures of the lumbar vertebral endplate in the etiology of low back pain. A hypothesis on the causative rol of spinal compression in a-specific low back pain. Medical Hypotheses, in press.

[111] Adams MA, McNally DS, Chinn H, Dolan P. Posture and compressive strength of the lumbar spine. Clinical Biomechanics 1994;9:5–14.

[112] Cyron BM, Hutton WC. The fatigue strength of the lumbar neural arch in spondyolysis. Journal of Bone and Joint Surgery-British Volume 1981;60B:234–8.

[113] Potvin JR, Norman RW, McGill SM. Reduction in anterior shear forces on the L4/L5 disc by the lumbar musculature. Clinical Biomechanics 1991;6:88–96.

[114] Adams MA, Hutton WC. Has the lumber spine a margin of safety in forward bending? Clinical Biomechanics 1986;1(4):3–6.

[115] Schipplein OD, Reinsel TE, Andersson GBJ, Lavender SA. The influence of initial horizontal weight placement on the loads at the lumbar spine while lifting. Spine 1995;20(17):1895–8.

[116] Davis KG, Marras WS, Waters TR. Reduction of spinal loading through the use of handles. Ergonomics 1998;41(8):1155–68.