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A biomechanical evaluation of five lifting techniques

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Five lifting methods which cover the range of techniques recommended by various back schools have been biomechanically analysed with a static sagittal-plane computer model. The analysis was performed with two load-types (compact and bulky) and three weights in the hands (44 N, 222 N and 400 N). The methods were compared in terms of predicted L5/S1 disc compression, low-back ligament strain and strength requirements at the shoulders, L5/S1, hip and knee joints. In general the method entailing a squat posture, straddle foot stance and flat back (oriented as when standing erect) yielded lower compressions, ligament strains and overall strength requirements than the other methods.

Keywords: Lifting, back, physiological effects

Introduction

Numerous recommendations have arisen from various back schools regarding the proper way to lift in order to avoid low-back problems. To date, though, there is very little quantitative information available that would allow one to evaluate the efficacy of the various techniques put forward.

Specifically, the research that is available relates to postures not totally representative of those advocated by back schools. For instance, Park and Chaffin (1974), Troup (1977), Garg and Herrin (1979) and Leskinen *et al* (1983) consider the biomechanical implications of stoop *vs* squat lifting, but the lifts used do not take into account recommendations regarding placement of the feet or orientation of the spine during the lift. Secondly, the studies report on just L5/S1 disc compression or temporal patterns of forces at the hands and reaction between the feet and the floor with no comment made on the strength requirements or low-back ligament strain potential for alternative lifting techniques.

The purpose of this study is to provide strength requirement and low-back ligament strain information as well as L5/S1 disc compression for lifting methods that reflect the recommendations of the various back schools. Such data will be directly applicable to the evaluation of the differential biomechanical stressfulness of alternative lifting techniques, particularly in regard to implications for the L5/S1 joint.

Upon in-depth review of a multitude of techniques advocated by various back schools, it was noted that each consisted of specific recommendations regarding one or more of the following four points:

1. placement of the feet,
2. whether the knees are bent or straight,
3. whether the back is held flat or is curved, and
4. placement of the hands on the load.

If a specific foot placement is recommended, it typically will be the straddle-stance in which one foot is placed at the side of the load and the other foot behind the load. The primary advantage cited is the increased stability afforded by a wider base (Imrie, 1982; Davies, 1978). The alternative foot placement consists of having the feet side-by-side; an arrangement hereafter referred to as a parallel foot stance.

Most authors recommend that a squat posture be assumed while lifting, i e, that the knees be bent since stoop lifting is claimed to be more hazardous to the lower-back (Asmussen *et al,* 1965; Adams and Hutton, 1982; Edgar, 1979; Leskinen *et al,* 1983). In spite of the recognised hazard, stoop lifting is said to still be a frequently used lifting technique (Brown, 1971; Park, 1973; Shepard, 1974; Stubbs, 1976, Saari and Wickstrom, 1978; Troup, 1979). Squat lifting is said to be preferable to stoop lifting for three reasons:

(1) squat lifting shifts the load to the legs which are stronger than the back and therefore better suited to lifting heavy loads,

(2) the load is closer to the body thereby reducing the moment arm (Bendix and Eid, 1983; Troup *et al,* 1983), and

(3) the low-back ligaments are exposed to a lower maximal strain (Anderson, 1983; Poulsen, 1981).

The stoop lifting method is considered preferable, though, in situations where the load is too wide to be placed between the knees since the stoop method minimises the moment arm of the load to the low-back (Frankel and Nordin, 1980; Garg and Herrin, 1979; Park and Chaffin, 1974; Leskinen *et al*, 1983; Troup *et al*, 1983) though this was not supported by the results of Bendix and Eid (1983).

Some authors also emphasise the necessity of keeping the back flat throughout the lift (Asmussen *et al*, 1965; Grandjean, 1975) while others either make no comment or suggest a slightly-rounded lumbar spine (Caillet, 1981). A flat back is one in which the spinal column is kept in the same configuration found when standing erect. In essence, the trunk is held rigid, thus forcing all torso flexion to occur at the hip joints. The American Back School (Apts, 1984) strongly recommends locking the back in this position because they feel that the greatest amount of muscle control of the trunk is achieved with the spinal configuration found in erect posture. The flat-back configuration also minimises the strain on the spinal ligaments posterior to the joint centres-of-rotation. The 'flat-back' recommendation is controversial in that some experts such as Farfan and colleagues (Farfan, 1975; Gracovetsky *et al*, 1981) argue that it is important to take advantage of the capability of the ligaments to partially relieve the musculature of their role in counteracting the moment about a joint due to the load in the hands and the weight of the body segments involved. From this perspective it is advantageous to flex the back and thus strain the ligaments, thereby engaging their inherent resistance to elongation for the purpose of supporting the load in the hands.

A fourth point discussed in some of the techniques is the hand-hold. If addressed, the recommendation typically is that one hand goes on the upper-outer corner of the load and the other hand is placed on the opposite lower-inner corner. In this paper this will hereafter be referred to as an oposition hand-hold. This hand-hold gives more stability to the object but causes a larger load on the lower hand than does the parallel hand-hold (Coury and Drury, 1982).

Though there are differences between techniques in terms of recommendations on these four points, there are also two basic similarities. First, all techniques emphasise that the load should be kept as close to the body as possible. This reduces the magnitude of the moment about the joint-centre, in particular the L5/S1 joint. Second, virtually all techniques recommend that the load be lifted in a slow and controlled manner. This reduces the moments due to inertia and facilitates the ability of the individual to react to unforeseen events such as slippery surfaces, awkward loads, etc.

Table 1: Summary of the five alternative lifting techniques

Method	Foot placement	Knee orientation	Back orientation
Stoop	Parallel	Straight	Curved
Parallel/flat	Parallel	Bent	Flat
Parallel/ curved	Parallel	Bent	Curved
Straddle/flat	Straddle	Bent	Flat
Straddle/ curved	Straddle	Bent	Curved

For the purposes of this study, five alternative lifting methods were defined in such a way that the biomechanical impact of the recommendations of the various back schools could be assessed. The specific recommendations for each method in terms of foot position, knee angle and back orientation are summarised in Table 1. In all cases the hands are assumed to be parallel to one another at the centre-line of the box along the bottom edges. The current biomechanical model utilised in this study is not suitable for analysing the opposition hand-hold.

It can be seen in Table 1 that the first method is the basic stoop lift. This method is then contrasted with the remaining four, which are all squat lifts. The last four methods also represent the four combinations of two alternative foot positions and two alternative back orientations.

Method

The biomechanical model created at the University of Michigan (Garg and Chaffin, 1975; Anderson, 1983) was utilised for analysis of the five lifting methods. It is a static model, so each method was approached as a sequence of static postures. For each point in the lift the model takes as input the body posture and load vector at the hands and computes moments at the major body articulations and forces acting about the lumbosacral joint. The outputs that were analysed as part of this study were L5/S1 compressive force, lumbosacral ligament strains and muscle moment requirements at the shoulders, L5/S1, hips and knees. Ligament strains were calculated for the following ligaments:

(1) lumbodorsal fascia,
(2) interspinous/supraspinous ligament,
(3) articular capsular ligaments,
(4) ligamentum flavum, and
(5) iliolumbar/sacrolumbar ligaments.

Their location is shown schematically in Fig. 1 as straight lines running between attachment points on L5 and the sacrum.

The muscle moment requirement can be thought of as a strength requirement for a particular muscle group. For comparative purposes, moment production (strength) capabilities of over 3000 industrial workers have been measured for a large number of local muscle groups throughout the body. The muscle moment requirement for each muscle group as predicted by the biomechanical model can then be interpreted in the light of the distribution of respective muscle group moment production capabilities for the male and female working populations. The comparison is presented in terms of the percent of each population capable of the required moment for each muscle group.

An experiment was performed in order to obtain the sequence of static postures and load vectors needed to biomechanically analyse the five alternative lifting methods. One young, healthy male subject performed the five lifts with two types of loads – compact and bulky – each of which weighed 89 N. The subject lifted the box from the floor to waist level in a slow and controlled manner. The compact box was a 31 cm cube while the bulky box was 62 cm deep by 66 cm wide by 46 cm high. A single load was used for the experiment but three loads were modelled on the computer. All of the back schools offer the same

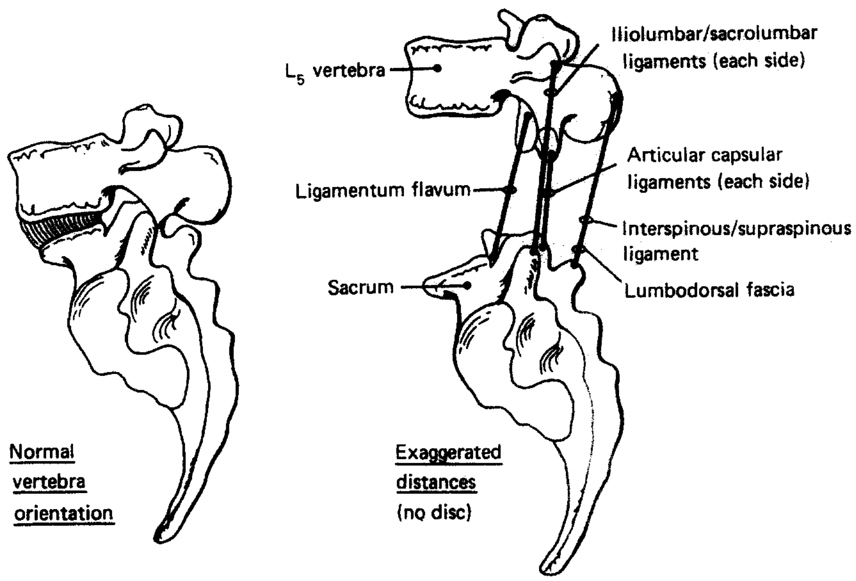

Fig. 1 Geometric representation of the low back ligament elements

recommendations regardless of the magnitude of the load to be lifted. Three replications of each lift were performed.

The subject was trained in each method by viewing videotape, film and/or slide/tape presentations by back schools representing each of the methods (other than the stoop method). He was then photographed in the sagittal plane at a distance of 5 m at a rate of three frames per second while performing each lift.

Reflective markers placed on the hand centre-of-gravity, elbow, shoulder, hip, knee and ankle joint centres were digitised from projections of the slides and used to calculate angular orientations of the various body segments for each point in the lift. Comparison of the hand locations between successive slides was used to calculate force vectors for the load. These data comprise the input to the biomechanical model. An example of the final sequence of static postures for a stoop lift and parallel-flat back lift with a compact box are illustrated in Figs. 2 and 3 respectively. Each drawing is a composite sagittal-plane view of the static postures adopted by the subject as he lifted from the floor to waist level.

When modelling the methods involving a straddle stance it was necessary to consider stresses on only the forward-most leg. The model assumes that both legs are in the sagittal plane, which is not exactly the case during a lift with a straddle foot stance. Often the rearward leg approaches the transverse plane in order to bring the load in close to the body. This complexity was handled by considering just the forward-most leg in the analysis.

The simplification does not affect estimates of the joint-specific strength requirements for joints above the knee. Also, estimates of the moment at the ankle and knee joints of one leg are dependent only upon the orientation of that particular leg. Since the model automatically divides the sum of the weight of the body above L5/S1 and the load equally between the two legs, ignoring the rearmost leg has no impact on predictions for the forward-most leg.

Three magnitudes of load in the hands (45 N, 222 N and 400 N) were modelled using the same postural and load vector data for each method and load-type. Since the load was lifted in a slow and controlled manner, inertial and acceleration effects were ignored in the computations.

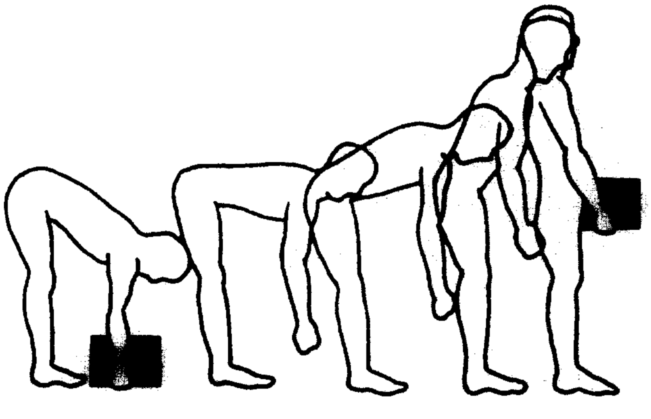

Fig. 2 Stoop lift

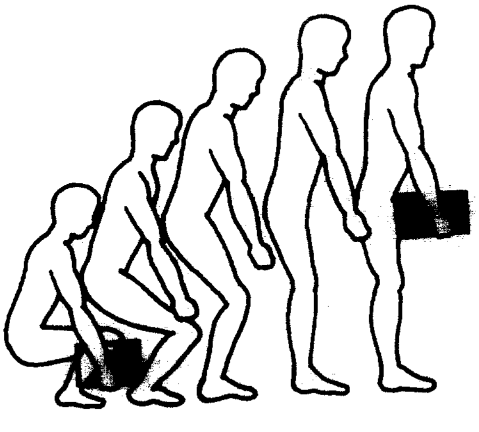

Fig. 3 Parallel stance/flat-back lift

Results

Tables 2, 3 and 4 summarise the maximum L5/S1 disc compression and lumbodorsal fascia strain, and minimum male percent capable across the L5/S1, shoulder, hip and knee muscle groups for each load, lifting method and load-

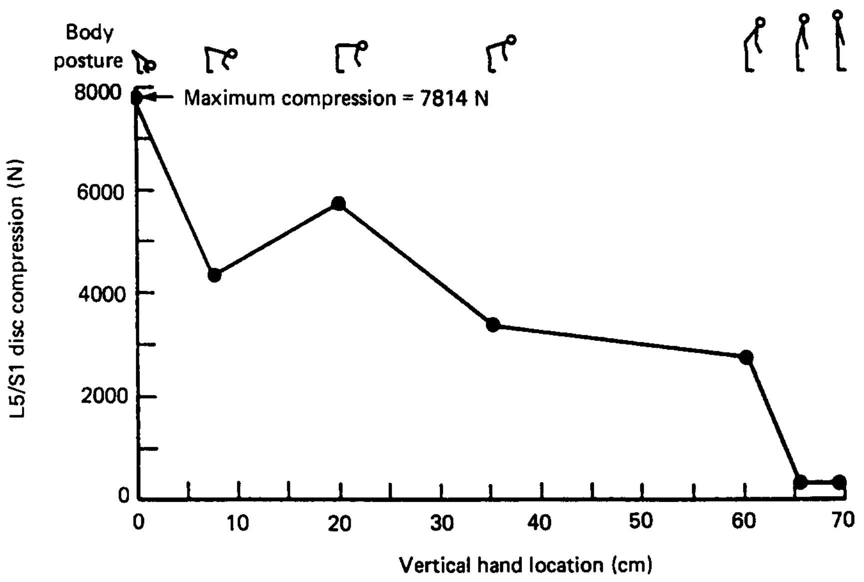

Fig. 4 L5/S1 disc compression *vs* vertical hand location for a stoop lift with a 400 N compact load

type combination. Each tabulated value reflects the extreme of the values calculated across all of the intermediate postures such as the two illustrated in Figs. 2 and 3 for a given experimental condition. The data reduction process is illustrated in Fig. 4 for L5/S1 compression. It can be seen that disc compression is graphed versus vertical hand height for the case of a stoop method to lift a 400 N compact box. The stick figures depict the body posture corresponding to the hand location. It can also be seen that the maximum compression is 7814 N, which is recorded in Table 2.

L5/S1 disc compression (Table 2) has been a standard measure of risk of low-back problems. The National Institute of Occupational Safety and Health (NIOSH) has set guidelines for manual lifting which recommend that no worker be required to lift loads that give rise to disc compression above 6361 N and that administrative controls be considered for lifts giving rise to compression greater than 3425 N (NIOSH, 1980). Review of Table 2 discloses that only the straddle stance/flat-back method keeps compression below 3425 N for compact loads up to 400 N. All bulky loads up to 400 N

Table 2: Maximum L5/S1 disc compression (N) and rank by lifting method, load-type and weight

	Compact load					
	44 N		222 N		400 N	
	L5/S1 disc compression (N)	Rank	L5/S1 disc compression (N)	Rank	L5/S1 disc compression (N)	Rank
Stoop	2439	4	4911	5	7814	5
Parallel stance/flat back	1361	1	2608	3	3871	3
Parallel stance/curved back	2595	5	3982	4	5407	4
Straddle stance/flat back	1428	2	2179	1	3092	1
Straddle stance/curved back	1735	3	2580	2	3432	2
	Bulky load					
	44 N		222 N		400 N	
	L5/S1 disc compression (N)	Rank	L5/S1 disc compression (N)	Rank	L5/S1 disc compression (N)	Rank
Stoop	2559	4	3926	3	5307	3
Parallel stance/flat back	2236	2	3560	2	5035	2
Parallel stance/curved back	2887	5	4932	5	7002	5
Straddle stance/flat back	2097	1	3147	1	4527	1
Straddle stance/curved back	2521	3	4355	4	6211	4

Table 3: Maximum lumbodorsal fascia strain (%) and rank by lifting method, load type and weight

	Compact load					
	44 N		222 N		400 N	
	% Strain	Rank	% Strain	Rank	% Strain	Rank
Stoop	4·6	3	3·5	3	2·6	3
Parallel stance/flat back	0	1	0	1	0	1
Parallel stance/curved back	5·6	4	4·6	4	3·7	4
Straddle stance/flat back	0	1	0	1	0	1
Straddle stance/curved back	0·1	2	0	2	0	2
	Bulky load					
	44 N		**222 N**		**400 N**	
	% Strain	**Rank**	**% Strain**	**Rank**	**% Strain**	**Rank**
Stoop	7·9	4	9·1	4	9·3	4
Parallel stance/flat back	0	1	0	1	0	1
Parallel stance/curved back	6·0	3	4·6	3	3·7	2
Straddle stance/flat back	0	1	0	1	0	1
Straddle stance/curved back	4·8	2	4·6	2	4·4	3

fall above the administrative level but the straddle-stance/flat-back method still gives the lowest compression.

In general, the flat-back methods yield lower compressive forces. The minimisation of disc compression comes about primarily because maintenance of a flat back requires more flexion at the hip joint which in turn means that the angle formed by the sacral endplate and the horizontal becomes more perpendicular. The increased inclination means that more of the load due to body weight and load in the hands becomes a shear force on the endplate rather than a compressive force. The predicted shear forces did not exceed 390 lbf (1735 N) which is well within failure limits of the articular facets such as given by Farfan *et al* (1976). Hence it is anticipated that there is a minimal risk damage due to the increased shear forces associated with the decreased compression associated with flat-back postures, at least for the healthy spine.

Low-back ligament strain offers another indicator of potential health risk. It was found that lumbodorsal fascia strain was the most severe of the five ligament groups for all experimental conditions so only strain values for this tissue are reported (Table 3). This finding is logical since, as can be seen in Fig. 1, the lumbodorsal fascia is one of the most-posterior ligaments to the joint centre-of-rotation. Thus it is strained the most for a given flexion. The other ligament at equal jeopardy, at least in terms of location, is the inter-spinous/supraspinous ligament, but it does not come on to tension until at least half-way through the range of flexion at the L5/S1 joint (Adams *et al,* 1980). Furthermore, the mechanical properties of fascia are such that relatively little strain to the tissue can cause damage compared with other ligaments in the low-back.

Jobs having lifts which give rise to lumbordorsal fascia strains above 5% have been found to have a fourteen-fold increase in low-back problems (Anderson, 1983). Clearly, those methods incorporating a flat-back (0% strain) result in minimum risk whereas methods involving a curved back can give rise to strains well above 5%. For instance, a stoop lift with a 400 N bulky box gives a strain of 9·26%.

Table 4 gives the minimum male percent of the population capable across the articulations of concern. For example, 96% of the male working population would be expected to have the strength to lift a 44 N compact load with a stoop lift method. NIOSH recommends that no lift should be required for which less than 25% of the male workforce would be capable. It can be seen that a number of lifting methods have percents capable below 25% at the 400 N load.

On the average the straddle stance methods give the maximum percent capable. As noted earlier, the knee of the rearward leg tends to be off to the side more with the straddle foot stance than with the parallel stance, thus allowing the load to be held closer to the body since the knees are not in the way. This factor reduces the moment requirements about the joints and thus more workers have the strength required to perform the lift. Due to the small amount of separation in the feet, though, for a straddle stance with a compact load there is less difference in stress/strain parameters for postures involving the straddle stance *vs* the parallel stance under compact load *vs* bulky load conditions. In other words, the beneficial effect of the straddle stance is most pronounced with bulkier loads that can still be brought between the knees.

Review of Tables 2, 3 and 4 together discloses that no one method optimises all criteria of stress and strain simultaneously. It can be seen that the flat-back methods minimise spinal ligament strain and disc compression and that the straddle-stance maximises percent capable in terms

Table 4: Minimum male percent capable across muscle groups at the shoulder, L5/S1, hip and knee joints and rank by lifting method, load-type and weight

	Compact load					
	44 N		**222 N**		**400 N**	
	Male % capable	**Rank**	**Male % capable**	**Rank**	**Male % capable**	**Rank**
Stoop	96	3	80	4	6	5
Parallel stance/flat back	95	5	68	5	7	4
Parallel stance/curved back	96	2	83	2	49	2
Straddle stance/flat back	97	1	91	1	61	1
Straddle stance/curved back	95	4	81	3	9	3

	Bulky load					
	44 N		**222 N**		**400 N**	
	Male % capable	**Rank**	**Male % capable**	**Rank**	**Male % capable**	**Rank**
Stoop	78	2	48	3	2	5
Parallel stance/flat back	62	4	50	2	36	2
Parallel stance/curved back	97	1	89	1	73	1
Straddle stance/flat back	64	3	46	4	31	3
Straddle stance/curved back	42	5	17	5	6	4

of strength. In general, the flat-back, straddle-stance lifting method yielded the best results in terms of minimising low-back ligament strain, L5/S1 disc compression and moment requirements about the articulations of the body.

It is interesting to note that even with a bulky load the stoop lift is never associated in this study with the least amount of stress or strain over the five lifting techniques investigated. This stands in contrast to the findings of a number of authors who state that the stoop lift may be preferable to the squat lift when lifting a bulky load (Frankel and Nordin, 1980; Garg and Herrin, 1979; Park and Chaffin, 1974; Leskinen *et al,* 1983; Troup *et al,* 1983). The discrepancy in results comes about by virtue of the fact that the squat lift technique used by the authors cited above did not allow the bulky load to be brought between the knees. When the stoop lift in this study is compared with the squat lift with parallel foot stance and curved back (the condition most representative of previous studies) it was found here also that the stoop lift is preferable of the two choices in terms of minimising back compression (Table 2). A squat lift can be advantageous, though, with a bulky load if a straddle-stance can be incorporated which allows the load to be brought between the knees. The findings of this study underscores the sensitivity of low-back stress to the horizontal location of the load relative to L5/S1.

Discussion

The results of this study corroborate the lifting guidelines given to industry in terms of the importance of keeping the load close to the body. The results also give additional support to two more controversial guidelines, namely:

(1) use a straddle-stance with a squat lift so that even bulky loads can be brought close to the body, and

(2) keep the back aligned as when standing erect throughout the lift.

Adoption of these guidelines appears, in general, to minimise the stresses on the disc, vertebra, muscles and ligaments of the low back and thus reduce the risk of injury

Further analysis is necessary to confirm these initial results. Future studies need to use a larger variety of experimental loads and multiple subjects of varied anthropometry. Also, inertial effects of the lifting motions need to be considered.

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