Work 21 (2003) 173–184
IOS Press

Low back pain and lifting: A review of epidemiology and aetiology

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Received 30 September 2002
Accepted 18 December 2002

Abstract. The incidence of low back pain has continued to increase in modern society, despite the considerable amount of scientific research that has aimed to isolate its exact aetiology. Although low back pain is still largely idiopathic, research has identified over one hundred risk factors for the condition. Of these risk factors, manual material handling tasks are perhaps the most widely explored within the biomechanical literature, as these tasks have been associated with high mechanical stresses on the lower back. Numerous technique-related variables have been addressed by researchers, whilst the influence of intra-abdominal pressure has also been considered. In addition to this, the implications of variations in the size and structural composition of the load have also been assessed. However, low back pain continues to pose a significant threat to the financial stability and happiness of millions of people worldwide. In addition, a number of functional work capacity assessment tests use lifting as a method for assessment of return to work condition. Many of these tests are not standardised and do not consider the implications of low back loading. Therefore new research attempts in this area are justified and should aim to identify the extent of the association that exists between the known risk factors and the incidence of low back pain.

Keywords: Low back pain, lifting, manual material handling, epidemic, cause

1. Introduction

It is well established within the literature that low back pain is a significant cause of functional disability in both the working population and the general public [41]. Over the past decade, research has consistently reported the lifetime prevalence of low back pain to be between 60 and 80 percent within the general population [13,38,71,87,120]. In addition to this, epidemiological evidence from the USA has suggested that approximately 20 percent of the general population is affected by low back pain each year, whilst the annual incidence rate in European countries is approximately 40 percent [100]. Epidemiological data presented for the UK and Canada is consistent with those studies conducted within the USA, indicating an annual incidence rate of 25% within the population [86].

In addition to the functional debilitation that is commonly associated with low back pain, there is also a major socioeconomic impact, as it is recognised as the single most expensive disorder of an occupational origin [26,41]. In an editorial written by Buchbinder, Jolley and Wyatt [6], it was estimated that the incidence of low back pain in 1994 cost the Australian public almost $400 million (all figures in US dollars). However, more recent evidence suggests that this figure has increased in recent years, with annual worker's compensation costs of almost $300 million [118] and $26 million [124] reported for the states of Victoria (Pop. 4.8 million) and South Australia (Pop. 1.5 million), alone. On an international level, the incidence of low back pain is reported to cost the United Kingdom 2.6 billion dollars each year [79], whilst the disorder reportedly costs the New Zealand public in excess of $93 million annually [1]. On a much larger and more significant

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scale, low back pain is reported to cost the USA between 15 and 30 billion dollars in lost wages, medical costs and lost productivity each year [35,67,87]. An estimated 11.4 billion dollars of this total is credited to workers compensation costs alone, whilst the remainder is attributable to indirect costs, such as the loss of productivity and the training of new workers [26].

Manual material handling tasks, such as lifting and lowering, pushing and pulling are considered to be major risk factors in the development of low back pain [21]. Research conducted in the USA by the Bureau of Labour Statistics [96] indicated that four out of five manual handling injuries occur in the lower back, with three of these injuries attributable to manual lifting tasks. The high rate of incidence and the socio-economic cost of industrially-related low back pain have stimulated the need for a better understanding of the manner in which such problems arise and how they may be controlled through better public awareness and improved workplace design. The purpose of this article is to present a review of the epidemiological and aetiological factors concerned with low back pain and lifting.

2. Methodology

2.1. Literature search

The research used in the compilation of this review was located using the Medline, PubMed and Sports Discus databases, in which a series of searches were performed for relevant papers published in English between 1980 and 2002. For the purposes of this review, keywords, such as lifting, low back pain, manual material handling and injury were entered into the search fields and combined to locate the most pertinent research. The results of this searching procedure were initially screened using the title of the relevant article as a guide and then further reduced based on the content of the abstract. Those papers that were considered to be primarily concerned with manual material handling tasks, such as lifting, and the prevalence and development of low back pain were selected for further examination. In addition to those papers collected from the bibliographic databases, several other pieces of literature cited in the retrieved articles were collected and used to compile this review .

2.2. Selection of dependent variables

Although previous research has suggested that an individual's anthropometry, surrounding environment, and psychological state may play an important role in the development of low back pain [67], only those papers concerned with mechanical risk factors, particularly lifting, were included in this review. This review discusses the different methods of lifting and their respective advantages and disadvantages, whilst also considering the differences that are inherent in the vertebral loads experienced during symmetrical and asymmetrical lifting tasks. Additionally, the potential influences of intra-abdominal pressure are investigated in this review as the role that this moment generating mechanism plays in spinal compression is still of some debate within the literature [15,18,78]. Finally, this review summarises the findings of previous research concerned with the effects of a change in the magnitude of the load, its dimensions, physical characteristics and relative positioning from the body, as each of these factors have been shown to affect the magnitude of mechanical loads [29,82,114].

3. Low back pain: Epidemiology and aetiology

Low back pain has been a common and widespread problem for decades and despite numerous efforts to limit its prevalence in modern society, the incidence of low back pain has continued to increase to near epidemic proportions [31,59,102]. Epidemiological research has consistently reported low back pain as the most frequent cause of activity limitation amongst those aged less than 45 years [85,100] and the third most frequent, behind arthritis and coronary heart disease beyond this age [75,108]. In a previous study, low back pain (LBP) was described as being an acute pain in the lumbar spinal region, localised below the belt line and above the gluteal sulcus, occurring intermittently or continuously over a period of two days or more [71]. Previous literature also suggests that it is not uncommon for sufferers of LBP to experience numbness, tingling or radiating pain down through the buttocks and the lower extremities due to soft tissue damage [62,71, 120]. Although some research has suggested that the onset of LBP typically occurs early in the third decade of life [40], other studies have suggested that the incidence of LBP tends to increase in early adolescence, possibly coinciding with puberty [9,70]. Researchers have established that the early incidents of LBP experienced in these adolescent years are related to those experienced in adult life [26,105]. As a consequence, these researchers suggest that a better understanding of the aetiology of LBP could be established if future research efforts concentrated on juvenile LBP, rather than the previously established LBP of adults [70,105].

Within the previous literature, it has been widely reported that the incidence of LBP increases with age, before reaching a plateau or declining around sixty to sixty-five years of age [8,26,71]. Conversely, it has been hypothesised that the degenerative changes attributable to osteoporosis, tend to cause females to experience LBP more frequently as they increase in age [40]. According to Lee and colleagues [71], the pain experienced as a result of LBP is more prolonged and disabling later in life, irrespective of gender.

Despite the large amount of scientific research that has been performed in this area, LBP is still considered idiopathic, due to the vast uncertainties that surround its aetiology [21,34,62,74,75,100]. However, due to the widespread prevalence and the socio-economic impact that it has on society, it has been an important aim of many of these studies to define the common risk factors associated with the development of LBP [42]. These investigations have generally implemented one of four common approaches when identifying these primary risk factors; an epidemiological approach; a physiological approach; a biomechanical approach; or a psychological approach [23]. In these investigations over one hundred risk factors have been established for LBP, however due to the multi-facetted nature of LBP the extent of their contribution to the disorder has been difficult to ascertain [67]. Separate researchers have presented contradictory results for most of the reported risk factors, questioning the reliability of the established relationship between each feature and the development of LBP [8].

Many epidemiological studies have suggested that disorders of the lower back develop as a result of a patient's personal characteristics and lifestyle, rather than their exposure to physical stressors [3]. However, previous investigations have also identified several mechanical risk factors to LBP and the most common of these is manual material handling (MMH), which encompasses tasks that involve lifting, lowering, pushing and pulling [22,46,107]. The inherent risk associated with MMH is reported to be greater for females [76] and is believed to increase when a movement involves excessive forward flexion [36,53,105] or spinal torsion [57,76,116]. It has been theorised that during the performance of these tasks, the lumbar spine is exposed to excessive compressive loads, which have the potential to hasten degenerative changes in the intervertebral discs or lead to fracturing of the intervertebral endplates [11,61,81,117].

4. Manual lifting tasks and injury

It has been sufficiently established within the previous literature that tasks involving manual material handling can have potentially hazardous implications on vertebral structures of the lumbar spine [49]. As many activities of daily life involve some form of manual material handling, specific research has concentrated on minimising the effects of lumbar loading, such that the risk of LBP may be reduced [37,121]. The following sections provide an overview of the literature pertaining to both symmetrical and asymmetrical lifting activities and also encompass the influence of intra-abdominal pressure, and the effects of different load designs on the magnitude of spinal loads.

4.1. Manual lifting tasks as a cause of low back pain

Due to the potential causative association that exists between MMH and low back pain, much of the biomechanical literature concerned with physical load handling has been directed towards the quantification of mechanical stresses in the lower back [20]. It has been well documented within the literature that the torsional and cumulative compressive loads that are often associated with bending and lifting tasks play a contributory role in the development of low back disorders [5,11,24, 72,73,99]. In addition to this, other authors have suggested that biomechanical variability in the handling of materials may also play an important role in the onset of low back pain [10,50,51,56,65]. In general, a typical lifting movement can be divided into two distinct phases; a loading phase, during which the subject exerts a vertical force on the object until it moves; and a lifting phase, which involved vertical displacement of the mass [114]. Previous research has indicated that the highest compressive and shearing forces are experienced during the early stages of the loading phase, generally within the first 0.2 to 0.4 seconds of the lift [23, 44,54]. During the performance of a lift, the body is affected by internal stresses, which result from internal pressures, the tautness of surrounding musculature and other passive components; and external stresses that are caused by the weight of the body segments, the length of the moment arms and the load itself [84]. In order to manage the combined weight of the load and body segments, it is necessary for an individual to produce an adequate amount of internal force to stabilise the trunk and manipulate the load [104]. Previous literature has suggested that the vertebral column copes with these internal forces by sharing the load amongst a number of structures within and surrounding the intervertebral joint, particularly the intervertebral discs, the facets, the ligaments and the musculature [47]. However, a separate study suggested that this notion was only plausible under specific circumstances, as the orientation of the vertebral bodies tends to differ between lifting techniques, consequently altering the size and shape of the adjoining surfaces [94].

For many years it has been advocated that the preferred method of lifting and lowering should be the leg or squat lift (Fig. 1), which is performed with the knees flexed and with the natural curvature of the spine maintained [103,108,116]. The universal prescription of this technique has been based on experimental evidence, which has suggested that this technique better distributes the load over the entire vertebral body [93], decreases compressive forces by shifting the stress from the lower back to the extremities [66,110], and reduces intervertebral shear forces [49]. In addition to these benefits, maintenance of the normal lordotic curve during lifting has been shown to limit the stress placed on the posterior ligaments of the back and is believed to share up to 40 percent of the compressive load with the facet joints [87,113]. A study conducted by Toussaint and colleagues [110] tested the concept of load transferal from the spine to the lower extremities during lifting tasks that utilised the leg lifting procedure. The results of this investigation indicated that the net knee moment was reduced during the performance of a leg lift, when compared with a back lift [110]. These results made it difficult to conclude that spinal loading was reduced during leg lifting, as the researchers had expected to see an increase in the net knee moment, if the load was, in fact, transferred to the legs [110]. Separate studies suggested that the compressive forces experienced during leg lifts, were only lower than those seen in other techniques when the object was elevated between the knees [97], as this positioned the load's centre of mass closer to the body [87].

Although most people are aware of the proposed method for safer lifting, there are very few tasks that can be performed whilst adhering to the guidelines of the leg lifting procedure [87,93]. As a result, individuals generally employ an alternate method of lifting in order to meet the demands of the specific task [55,87].

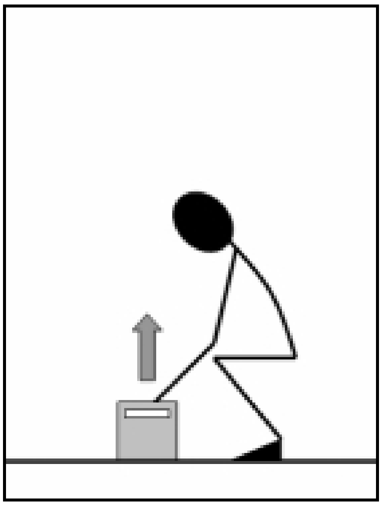

Fig. 1. The leg lifting technique.

An alternate lifting technique that is commonly used is the back lift (Fig. 2), which is performed with the knees in extension, whilst the hips and lumbar spinal regions flex forward [49,55]. It has been suggested that this technique places the spine in a vulnerable position, placing the trunk at a muscular disadvantage [98], consequently leading to high levels of compression [28, 103,106]. The excessive forces associated with this technique have often been connected with injuries of the posterior intervertebral ligaments [2,27] and prolapse of the intervertebral discs [29,45,105]. Contrary to these results, other biomechanical analyses have suggested that this technique actually results in slightly less spinal compressive forces than the leg lift technique [21,29,34]. In fact, previously presented results suggested that the forces occurring at the lumbosacral joint (L5/S1) during a leg lift can be as much as 50 percent higher than the back lift, when the load is lifted away from the body [45]. In addition to this, epidemiological data and occupational assessment has suggested that individuals prefer to back lift rather than leg lift [87, 116]. Several comparative analyses of these two techniques suggest that this preference is based on an increase in the perceived physiological cost of the leg lift technique due to the need to raise the load and trunk vertically [94,108,111]. Separate research has addressed the role of the spinal musculature in back lifting and found that the electrical activity declined markedly as the spine approached full flexion; this phenomenon is known as flexion-relaxation [87,109]. Whilst the spine is in this flexed position the load is fully supported by the spinal ligaments, requiring little to no energy expenditure and consequently limiting the negative effects of

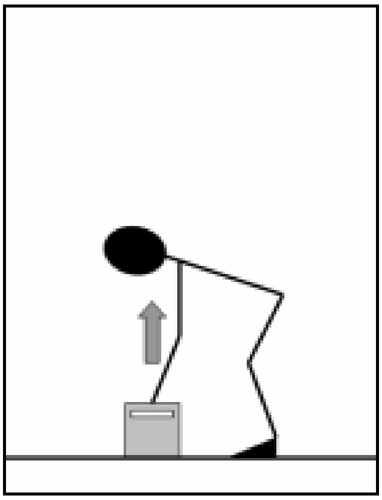

Fig. 2. The back lifting technique.

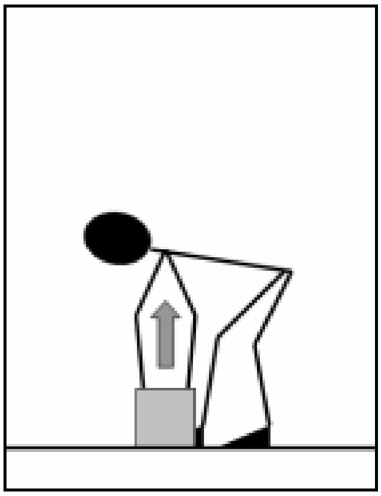

Fig. 3. The freestyle lifting technique.

fatigue [87,109]. Investigators have observed the effects of fatigue on lifting technique and have noted a 31 percent decrease in lifting power [107] and a tendency for individuals to shift from a leg lift technique to a back technique, supporting the evidence presented for the apparent metabolic efficiency of back lifting [7, 107,116].

Although much of the biomechanical literature is confined to the assessment of the two lifting techniques that have been discussed, there are several researchers that have addressed a freestyle lifting technique [45, 97]. The results of these studies suggested that, if given the choice, an individual would choose to lift a load with a technique that they felt best suited their style of movement [45,97]. This technique was visually described as being a combination of the leg and the back lifting techniques (Fig. 3) and was alleged to have been selected to minimise the perceived strain of the lift, whilst saving both time and energy [97].

Despite the fact that much of the biomechanical literature has been concerned with the effect of the different lifting techniques on spinal loading, many researchers have suggested that the speed at which the load is raised may also play an important role in lumbar loading and the prevalence of low back pain [30,44,48,58,69,87, 111]. Results from some of these studies suggest that when a lift is performed quickly, the magnitude of the compressive and shearing forces, the torque and the myoelectrical activity are directly affected and tend to increase in magnitude [30,44,58,69]. Conversely, other studies have presented results, which suggest that awkward and heavy loads place greater stress on the intervertebral joints when the lift is performed at a slower speed and consequently should be performed as fast as possible [48,77,87,111]. This suggestion was based on the notion that the annulus of the intervertebral disc is the main load bearing structure of the joint and its ability to safely bear excessive loads decreases with time [48]. Despite the contrasting results, most of the literature tends to agree that whilst the vertebral column is moving under load, the individual should avoid any sudden changes in movement, as this can result in momentary, yet potentially injurious overloading of the lower back structures [86].

Whilst it has clearly been established that the lifting of a load plays an important role in the aetiology of low back pain, it is necessary to also consider the implications of lowering a load of the same magnitude to a lower surface. Previous research indicates that 52 percent of all manual handling tasks are lowering in nature and two out of every three musculoskeletal injuries occur during lowering activities [68]. With this in mind, it is interesting to note that lowering tasks are less physiologically demanding than lifting tasks [16, 23] and intra-abdominal pressure is lower [23,72]. In addition to this, the force generated by the trunk extensor muscles during lowering activities has been shown to be almost 50 percent less than the force generated during lifting movements, independent of trunk asymmetry [16]. Although some research has indicated that compressive forces are higher in lowering tasks [16], most of the literature tends to suggest that lower compressive forces are experienced during lowering activities [23,112].

The body of knowledge that now exists regarding low back pain and its association with lifting has led to the realisation that there is a clear need for biomechanically accurate methods for determining the magnitude of specific forces that can safely be borne by structures of the spine [122]. One of the first cited recommendations was made by the International Labour Office in 1967, who suggested that a load of 50 kg should be considered the maximal mass to be lifted by a healthy adult male [111]. However, the calculation of this maximum load failed to take into consideration the size of the load and the distance that its centre of gravity was positioned from the body's centre of mass and consequently was ineffective in reducing the magnitude of potentially injurious stresses [111]. Over a decade later, the National Institute for Occupational Safety and Health (NIOSH) developed an equation that was used to predict the 3433N safety limit that is often promoted as the upper limit of spinal compression that can safely be endured by the majority of the working population [91]. However, there was stipulation that the criteria on which the formula was derived did not agree with the findings of current biomechanical literature and as a result, could not accurately predict safe loading limits [48]. As a result of these claims, the guidelines of the NIOSH lifting equation were revised to correspond better to the finding of biomechanical research and to take into account, amongst other things, the dynamic nature of lifting movements [123]. Despite the improvements made in the revised equation, it has been suggested that the equation needs to consider other additional factors, such as the velocity of the performance and the degree of asymmetry involved in the lift, in order to accurately present guidelines for safer manual load handling [69,80].

4.2. *Loading characteristics of symmetrical and asymmetrical lifting tasks*

Although lifting has been recognised as a primary risk factor in low back pain for many years, the concept of lifting asymmetry is relatively new and has recently started to receive a substantial amount of interest in the lifting research [21,43,61,64,80,117]. Gagnon and colleagues [43] defined an asymmetrical lift as one that involves rotation of the shoulders relative to the hips or has the trunk deviate from the sagittal plane. Epidemiological research has shown that when a lifting task is performed asymmetrically there is an increase in the risk of low back pain and intervertebral disc herniation [64,117]. It is often argued that this increased risk is due to the increased muscle co-activity [80,117] higher compressive [80,117] and shear forces [80] experienced during asymmetrical lifting activities when compared with symmetrical lifting activities. As a result of the potential relationship between asymmetrical lifting and low back pain, the revised NIOSH lifting equation incorporated a modulation factor for asymmetrical lifting [123]. This modulation factor mediates lifting limits by 10 percent for every 30° of asymmetry involved in the movement, regardless of the whether the lift origin is left of the sagittal plane or right of the sagittal plane [123]. The findings of the study conducted by Marras and Davis [80] suggested that these guidelines were over-simplified and should take into consideration the hands being used to perform the task; the direction of the movement and a non-linear modulation factor for two-handed lifting tasks that involve more than 60° of asymmetry. These suggestions were based on the findings of their study, which indicated that compressive forces were only increased in asymmetric lifting when the load was being lifted with both hands or, to a lesser extent, when the load was being transferred across the body with a single hand [80]. Their findings also suggested that spinal compression was lower when the lift originated from the right of the sagittal plane and tended to increase as a function of asymmetry to 60°, after which it increased disproportionately [80]. The discrepancy noted between the left and the right hand origin of the lift and the magnitude of spinal compression may be partially explained by anatomical data presented by McGill et al. [88]. With the aid of CT scans, McGill and colleagues [88] reported that the cross-sectional area of the erector spinae, external oblique and internal oblique were 10 to 14 percent smaller on the right-hand side of the body, whilst the rectus abdominis was 11 percent larger on the right-hand side.

In an occupational setting, research has indicated that workers tend to adopt an asymmetric posture when lifting heavier loads, due to the improved mechanical advantage that they receive in these positions [43]. Additionally, the twisting movements that are used during asymmetrical lifting activities have been found to require less energy than foot movements such as stepping or shuffling, adding to the perceived benefits of this lifting style [43]. The use of this technique can be justified in terms of the perceived advantage that it offers an individual, however, it cannot be justified mechanically, as research suggests that the structures of the spine are not adapted to supporting large forces in these positions [43,64]. In a study performed by Ueno and Liu [113] the results indicated that the number of annular fibres used to resist a compressive load on the intervertebral disc decreased when the spine was rotated. This possibly suggests that the intervertebral disc is more vulnerable to damage during asymmetrical lifting tasks when compared with symmetrical lifting tasks, even when spinal compression is maintained at a constant level [5,43]. Gagnon and colleagues [43] concluded that pivoting with the load was a safer way of manually transferring materials, as it tended to minimise the effects of the muscular imbalances induced by the asymmetry of the task.

Several researchers have advocated that an asymmetrical lifting technique would be preferred over the symmetrical back and leg lifting techniques, if the asymmetrical technique limited trunk flexion and maintained the load as close to the body as possible [4]. It was suggested that the asymmetrical straddle-legged lift, which involves the placement of one foot beside the load and the other behind it (similar to the technique shown in Fig. 3), was successful in meeting these criteria and consequently had the potential to reduce the loading on the lower back [4]. However, in a recent study, the straddle-legged lift was found to have no significant effect on spinal compression when compared with a symmetrical back lift and a free lift, but was significantly better than the symmetrical leg lift [21]. The authors concluded that the benefits provided by the straddle-legged lifting technique were only marginal, but suggested that the technique provided a good basis of support and thus may be beneficial under conditions that challenge an individual's balance [21].

4.3. The influence of intra-abdominal pressure on vertebral loading

It has been well established that lifting and lowering tasks can place the lumbar spine under a series of physical stresses, which are potentially injurious and can lead to the onset of a low back disorder [11,24, 99]. However, much of the previous literature indicates that there is a significant increase in intra-abdominal pressure during the performance of strenuous lifting tasks [15,101,108]. Many researchers have advocated that this increase in pressure helps to stabilise the lumbar spine against the large flexion forces induced by the initial acceleration of the load [12,60,87]. The increase in intra-abdominal pressure occurs as a result of the synchronised activation of the abdominal muscles, the diaphragm and the muscles of the pelvic floor [95,101, 112]. Previous investigations have indicated that the diaphragm is the most important muscle involved in increasing intra-abdominal pressure, whilst the musculature of the pelvic floor and the oblique muscles appear less important [60]. Additional studies also indicated that the transversus abdominis was active during lifting tasks and played an important role in the production of intra-abdominal pressure [14,108]. It was advised by Norris [95], that in a lifting activity that involved the contraction of the rectus abdominis, both the intra-abdominal pressure and flexion torque would rise, consequently increasing the compressive forces placed on the lumbar spine.

Research that has compared the differences in intra-abdominal pressure between the leg and back lifting techniques has indicated that the magnitude of intra-abdominal pressure tends to be higher when the trunk is flexed during the back lift [45,63,75,87,112]. Only one of the reviewed investigations found the intra-abdominal pressure to be greater during a leg lift when compared with the back lift [89]. The above studies compared the differences in intra-abdominal pressure evident between different lifting techniques, but the relationship that exists between intra-abdominal pressure and lowering is equally important, as some forces can be expected to be higher in lowering than in lifting [15]. Research investigations that compared the differences in intra-abdominal pressure during lifting and lowering tasks have shown that the pressure measured during lifting tasks was much higher than that recorded during lowering tasks [15,23,72]. It was hypothesised by Cresswell and Thorstensson [15] that the higher intra-abdominal pressure observed during lifting activities may have been the result of a greater need for truncal stability during lifting activities. This notion is supported by evidence that has indicated that low back pain patients have higher levels of intra-abdominal pressure than asymptomatic individuals [71,112].

4.4. Load variability and its effects on forces within the vertebral column

The physical stresses associated with lifting are known to be dependent not only on the magnitude of the load, but on its dimensions, physical characteristics and its relative position to the body [97]. Due to this relationship, a substantial amount of the biomechanical research has addressed the effect that load placement [29,64,108], load characteristics [17,39,83] and load knowledge [13,114] has on vertebral loading. Previous research has reported that when the load is placed at a greater horizontal distance from the body's centre of gravity, the compressive forces acting on the lumbar spine increase [29,64,97]. Similarly, researchers have observed that lifting a load that has been placed between the feet at a horizontal distance of zero from the body's centre of gravity also leads to a slight increase in lumbar flexion and spinal compression [29]. It is suggested that this increase in spinal compression is the result of an increase in the length of the moment arm acting at the lumbosacral joint [83] and for this reason, it has been advised to lift the load from a comfortable horizontal location and keep it as close to the body as possible for the entire duration of the lift [108]. However, the ability to keep the centre of the load close to the body during a dynamic lifting task is directly affected by its physical characteristics and its dimensions [17, 83]. In an assessment of manual material handling in an industrial setting, it was found that the median box size was $28.0 \times 20.5 \times 21.5$ cm for length, width and height respectively [33]. Previous research observed that as the size of the load was increased, the bending torque and extensor moment arm were also increased, consequently intensifying lumbosacral compression [29,39, 83].

In an occupational setting, the expected mass of the load is often based on its visual appearance, but it has been shown through research that to estimate the mass of a load on the basis of its size is not always accurate and can potentially result in injury [13]. It is well established that as the magnitude of the load increases, the resulting moments acting at L5/S1 are also increased [39,64,83]. However, previous investigations have suggested that the lumbar spine is subject to larger forces when the true mass of the load is unknown prior to lifting, especially when the effort exerted is greater than the effort required [13,19]. During lifting tasks, where the actual mass of the load is under-estimated, an increased level of muscle co-activity was observed and tended to be twice as high as the activity recorded under expected loading [52,66]. Research has also indicated that the loading pattern observed under these conditions tends to resemble the pattern recorded whilst lifting the actual load, despite the noticeable difference in the mass of the loads [13]. In similar situations, where the mass of the load was under-estimated, it was found that lifting unexpectedly heavy loads had little to no effect on the technique used or the loading of the lumbar spine when compared with the equivalent expected lifts [114,115].

Another load characteristic that has received a great deal of interest in the previous [32,39] and current literature [17,83] is the presence of handles on the load. The earlier research in this area indicated that both vertical ground reaction forces and lumbosacral compression increased at a faster rate and reached higher peak values, when a load was lifted with handles [32, 39]. In addition to this, a separate investigation found that the use of cut-out handles actually decreased the maximum amount of the load that could be lifted by subjects during a series of carrying tasks [90]. In the study conducted by Freivalds and colleagues [39], their conclusions were based on the observed loading patterns that resulted from erector spinae activity. However, Davis et al. [17] and Marras et al. [83], indicate that there was no consideration made for antagonistic musculature, such as the external oblique and the rectus abdominis and consequently did not sufficiently emulate the conditions observed in an industrial setting. In their respective studies, Davis et al. [17] and Marras et al. [83] found that the inclusion of handles on the load significantly reduced compressive and antero-posterior shearing forces at the lumbosacral joint when compared with no-handle lifting. The decreased stresses acting on the lumbar spine were said to be due to the improved ability to bring the load closer to the body [83] and the lower muscular activity in the rectus abdominis during lifting with handles [17]. The lower compressive loads experienced during lifting with handles, are supported by previous research that suggests that high levels of rectus abdominis activity during lifting, increases flexion torque and consequently spinal compression [95]. Additionally, it is also possible that the inclusion of handles increases the height of the initial lift, which research has suggested, significantly decreases compression at the lumbosacral joint [64,83,92].

5. Summary

Despite the number of relatively recent and sometimes comprehensive reviews [25,38,116,119,122] on manual material handling and the aetiology of low back pain, none have specifically concentrated in detail upon the issues associated with a lifting and lowering task. In more recent years, it has become evident that many countries are now utilising complex work capacity assessment tests in order to ascertain whether or not a worker should return to work after low back pain problems [61]. Many of these tests are not standardised and require subjects to lift various loads in various combinations of tasks [61]. For example, a current component of a work capacity assessment task within Australia, which is used by employers for return to work assessment, is to lift a box containing up to 25 kg onto a bench and then lower it again. During the task no instruction on correct lifting technique is given and there is no accommodation for subject anthropometry, age or gender. Consequently, further research on the functionality of these tests is urgently needed and a review of literature pertaining to low back pain and lifting is a useful prerequisite for any researcher who wishes to examine and make recommendations in this area.

Acknowledgement

Workplace Services, Adelaide, Australia.

References

[1] Accident Compensation Corporation, Preventing low back injuries: Literature review, Available at: http://www.acc.org.nz/acc-publications/pdfs/ip/backs-literaturereview-(998.pdf), 1998, Accessed June 25, 2002.
[2] M.A. Adams and W.C. Hutton, Has the lumbar spine a margin of safety in forward bending? *Clinical Biomechanics* **1** (1986), 3–6.
[3] M.A. Adams, A.F. Mannion and P. Dolan, Personal risk factors for first-time low back pain, *Spine* **24**(23) (1999), 2497–2505.
[4] C.K. Anderson and D.B. Chaffin, A biomechanical analysis of five lifting techniques, *Applied Ergonomics* **17** (1986), 2–8.
[5] A. Bhattacharya and D.N. Ghista, Biomechanical guidelines for determining the limiting values of occupational task involving torsional loading of the spine, in: *Biomechanics IX-B*, D.A. Winter, ed., Champaign, IL: Human Kinetics Publishers, 1985, pp. 60–65.
[6] R. Buchbinder, D. Jolley and M. Wyatt, Breaking the back of back pain, *The Medical Journal of Australia* **175** (2001), 456–457.
[7] T.A. Buhr and D.B. Chaffin, *Leg muscle strength as a limiting factor in lifting tasks*, in 21st Annual Meeting of the American Society of Biomechanics, Clemson, South Carolina: Clemson University, 1997, pp. 91–92.
[8] A. Burdorf and G. Sorock, Positive and negative evidence of risk factors for back disorders, *Scandinavian Journal of Work, Environment and Health* **23** (1997), 243–256.
[9] A.K. Burton, R.D. Clarke, T.D. McClune and K.M. Tillotson, The natural history of low back pain in adolescents, *Spine* **21** (1996), 2323–2328.
[10] A.H. Chang, W.A. Lee and J.L. Patton, Practice-related changes in lumbar loading during rapid voluntary pulls made while standing, *Clinical Biomechanics* **15** (2000), 726–734.
[11] C.K. Cheng, H.H. Chen, H.H. Kuo, C.L. Lee, W.J. Chen and C.L. Liu, A three-dimensional mathematical model for predicting spinal joint force distribution during manual lifting, *Clinical Biomechanics* **13**(**Supplement 1**) (1998), S59–S64.
[12] J. Cholewicki and S.M. McGill, Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain, *Clinical Biomechanics* **11**(1) (1996), 1–15.
[13] D.A.C.M. Commissaris and H.M. Toussaint, Load knowledge affects low-back loading and control of balance in lifting tasks, *Ergonomics* **40**(5) (1997), 559–575.
[14] A.G. Cresswell, Responses of intra-abdominal pressure and abdominal muscle activity during dynamic trunk loading in man, *European Journal of Applied Physiology and Occupational Physiology* **66** (1993), 315–320.
[15] A.G. Cresswell and A. Thorstensson, Changes in intra-abdominal pressure, trunk muscle activation and force during isokinetic lifting and lowering, *European Journal of Applied Physiology and Occupational Physiology* **68** (1994), 315–321.
[16] K.G. Davis, W.S. Marras and T.R. Waters, Evaluation of spinal loading during lowering and lifting, *Clinical Biomechanics* **13**(3) (1998), 141–152.
[17] K.G. Davis, W.S. Marras and T.R. Waters, Reduction of spinal loading through the use of handles, *Ergonomics* **41**(8) (1998), 1155–1168.
[18] P.R. Davis, The use of intra-abdominal pressure in evaluating stresses on the lumbar spine, *Spine* **6** (1981), 90–92.
[19] M.P. de Looze, M.C. Boeken-Kruger, S. Steenhuizen, C.T.M. Baten, I. Kingma and J.H. van Dieën, Trunk muscle activation and low back loading in lifting in the absence of load knowledge, *Ergonomics* **43**(3) (2000), 333–344.
[20] M.P. de Looze, J.B.J. Bussmann, I. Kingma and H.M. Toussaint, Different methods to estimate total power and its components during lifting, *Journal of Biomechanics* **25**(9) (1992), 1089–1095.
[21] M.P. de Looze, P. Dolan, I. Kingma and C.T.M. Baten, Does an asymmetric straddle-legged lifting movement reduce the low-back load? *Human Movement Science* **17** (1998), 243–259.
[22] M.P. de Looze, I. Kingma, W. Thunnissen, M.J. van Wijk and H.M. Toussaint, The evaluation of a practical biomechanical model estimating lumbar moments in occupational activities, *Ergonomics* **37**(9) (1994), 1495–1502.
[23] M.P. de Looze, H.M. Toussaint, J.H. van Dieën and H.C.G. Kemper, Joint moments and muscle activity in the lower extremities and lower back in lifting and lowering tasks, *Journal of Biomechanics* **26**(9) (1993), 1067–1076.
[24] A. Delisle, M. Gagnon and P. Desjardins, *An approach to estimate workers' stability in manual materials handling*, in Canadian Society for Biomechanics IXth biennial conference, Burnaby, British Columbia: Canadian Society for Biomechanics, 1996, pp. 76–77.
[25] P.G. Dempsey, A critical review of biomechanical, epidemiological, physiological and psychophysical criteria for designing manual material handling tasks, *Ergonomics* **41**(1) (1998), 73–88.
[26] P.G. Dempsey, A. Burdorf and B.S. Webster, The influence of personal variables on work-related low-back disorders and Implications for future research, *Journal of Occupational and Environmental Medicine* **39**(8) (1997), 748–759.
[27] P. Dolan and M.A. Adams, Influence of lumbar and hip mobility on the bending stresses acting on the lumbar spine, *Clinical Biomechanics* **8** (1993), 185–192.
[28] P. Dolan and M.A. Adams, The relationship between EMG activity and extensor moment generation in the erector spinae muscles during bending and lifting activities, *Journal of Biomechanics* **26**(4/5) (1993), 513–522.
[29] P. Dolan, M. Earley and M.A. Adams, Bending and compressive stresses acting on the lumbar spine during lifting activities, *Journal of Biomechanics* **27**(10) (1994), 1237–1248.
[30] P. Dolan, I. Kingma, J.H. van Dieën, M.P. de Looze, H.M. Toussaint, C.T.M. Baten and M.A. Adams, Dynamic forces acting on the lumbar spine during manual handling: Can

they be estimated using electromyographic techniques alone? *Spine* **24**(7) (1999), 698–703.

[31] G. Drouin, D. Gagnon and A. Ghorbal, *Estimation of 3D moments at L5/S1 using a dynamometric box: a comparative validation study*, in 21st Annual Meeting of the American Society of Biomechanics, Clemson, South Carolina: Clemson University, 1997, pp. 97–98.

[32] C.G. Drury, J.M. Deeb, B. Hartman, S. Wooley, C.E. Drury and S. Gallagher, Symmetric and asymmetric manual materials handling. Part 1: Physiology and psychophysics, *Ergonomics* **32** (1989), 467–489.

[33] C.G. Drury, C. Law and C.S. Pawenski, A survey of industrial box handling, *Human Factors* **24** (1982), 553–565.

[34] J. Ekholm, U.P. Arborelius and G. Nemeth, The load on the lumbo-sacral joint and trunk muscle activity during lifting, *Ergonomics* **25**(2) (1982), 145–161.

[35] E.H. Elliot, J. Hamill and T.R. Derrick, *The influence of multiple lifts on load kinematics*, in Canadian Society for Biomechanics VIIIth biennial conference, Calgary: Canadian Society for Biomechanics, 1994, pp. 142–143.

[36] M.A. Esola, P.W. McClure, G.K. Fitzgerald and S. Siegler, Analysis of lumbar spine and hip motion during forward bending in subjects with and without history of low back pain, *Spine* **21**(1) (1996), 71–78.

[37] F.A. Fathallah, W.S. Marras, M. Parnianpour and K.P. Granata, A method for measuring external spinal loads during unconstrained free-dynamic lifting, *Journal of Biomechanics* **30**(9) (1997), 975–978.

[38] J.W. Frank, M.S. Kerr, A.S. Brooker, S.E. Demaio, A. Maetzel, H.S. Shannon, T.J. Sullivan, R.W. Norman and R.P. Wells, Disability resulting from occupational low back pain. Part 1: What do we know about primary prevention? A review of the scientific evidence on prevention before disability begins, *Spine* **21**(24) (1996), 2908–2917.

[39] A. Freivalds, D.B. Chaffin, A. Garg and K.S. Lee, A dynamic biomechanical evaluation of lifting maximum acceptable loads, *Journal of Biomechanics* **17**(4) (1984), 251–262.

[40] J.W. Frymoyer and A. Nachemsom, Natural history of low back disorders, in: *The adult spine: principles and practice*, J.W. Frymoyer, T.B. Ducker, N.M. Hadler, J.P. Kostuik, J.N. Weinstein and T.S. Whitecloud, eds, New York: Raven Press, Ltd., 1991, pp. 1537–1550.

[41] J.W. Frymoyer, M.H. Pope, J.H. Clements, D.G. Wilder, B. MacPherson and T. Ashikaga, Risk factors in low-back pain: An epidemiological survey, *The Journal of Bone and Joint Surgery* **65A**(2) (1983), 213–218.

[42] J.W. Frymoyer, M.H. Pope, M.C. Costanza, J.C. Rosen, J.E. Goggin and D.G. Wilder, Epidemiologic studies of low-back pain, *Spine* **5**(5) (1980), 419–423.

[43] M. Gagnon, A. Plamondon and D. Gravel, Pivoting with the load: an alternative for protecting the back in asymmetrical lifting, *Spine* **18**(11) (1993), 1515–1524.

[44] M. Gagnon and G. Smyth, Biomechanical exploration on dynamic modes of lifting, *Ergonomics* **35**(3) (1992), 329–345.

[45] A. Garg and G.D. Herrin, Stoop or squat: A biomechanical and metabolic evaluation, *AIIE Transactions* **11**(4) (1979), 293–302.

[46] V.K. Goel, S.J. Fromknecht, K. Nishiyama, J. Weinstein and Y.K. Liu, The role of lumbar spinal elements in flexion, *Spine* **10**(6) (1985), 516–523.

[47] V.K. Goel, J.M. Winterbottom, J.N. Weinstein and Y.E. Kim, Load sharing among spinal elements of a motion segment in extension and lateral bending, *Journal of Biomechanical Engineering* **109**(4) (1987), 291–297.

[48] S. Gracovetsky, Determination of safe load, *British Journal of Industrial Medicine* **43** (1986), 120–133.

[49] K.P. Granata, *Structural injury tolerance of the spine: Stability and lumbar lordosis in lifting*, in Third North American Congress on Biomechanics, combined with the Twenty-second Annual Conference of the American Society of Biomechanics and the Tenth Biennial Conference of the Canadian Society of Biomechanics, Waterloo: NACOB, 1998, pp. 373–374.

[50] K.P. Granata and W.S. Marras, *Variability in trunk and spinal loads during repeated lifting exertions*, in 21st Annual Meeting of the American Society of Biomechanics, Clemson, South Carolina: Clemson University, 1997, pp. 95–96.

[51] K.P. Granata, W.S. Marras and K.G. Davis, Variation in spinal load and trunk dynamics during repeated lifting exertions, *Clinical Biomechanics* **14** (1999), 367–375.

[52] K.P. Granata, K.F. Orishimo and A.H. Sanford, Trunk muscle coactivation in preparation for sudden load, *Journal of Electromyography and Kinesiology* **11** (2001), 247–254.

[53] K.P. Granata and S.E. Wilson, Trunk posture and spinal stability, *Clinical Biomechanics* **16** (2001), 650–659.

[54] D.W. Grieve, Dynamic characteristics of man during crouch- and stoop-lifting, in: *Biomechanics IV*, R.C. Nelson and C.A. Morehouse, eds., Baltimore: University Park Press, 1974, pp. 19–29.

[55] D.W. Grieve, The dynamics of lifting, *Exercise and Sport Sciences Reviews* **5** (1977), 157–179.

[56] P.M. Grills, R.P. Wells and R.W. Norman, *Variability of low back loads from a biomechanical model*, in VIIIth Biennial Conference, Calgary: Canadian Society of Biomechanics, 1994, pp. 198–199.

[57] M. Hakkanen, E. Viikari-Juntura and E. Takala, Effects of changes in work methods on musculoskeletal load. An intervention study in the trailer assembly, *Applied Ergonomics* **28**(2) (1997), 99–108.

[58] S.J. Hall, Effect of attempted lifting speed on forces and torque exerted on the lumbar spine, *Medicine and Science in Sports and Exercise* **17**(4) (1985), 440–444.

[59] R.G. Hazard, V. Reeves, J.W. Fenwick, B.C. Fleming and M.H. Pope, Test-retest variation in lifting capacity and indices of subject effort, *Clinical Biomechanics* **8** (1993), 20–24.

[60] B. Hemborg and U. Moritz, The causal factors of the intraabdominal pressure rise during lifting, in: *Biomechanics X-A*, B. Jonsson, ed., Champaign, IL: Human Kinetics Publishers, 1987, pp. 183–187.

[61] E. Innes and L. Straker, Validity of work-related assessments, *Work* **13**(2) (1999), 125–152.

[62] A.I. King, Injury to the thoraco-lumbar spine and pelvis, in: *Accidental Injury: Biomechanics and Prevention*, A.M. Nahum and J.W. Melvin, eds, New York: Springer-Verlag, 1993, pp. 429–459.

[63] I. Kingma, C.T.M. Baten, P. Dolan, H.M. Toussaint, J.H. van Dieën, M.P. de Looze and M.A. Adams, Lumbar loading during lifting: a comparative study of three measurement techniques, *Journal of Electromyography and Kinesiology* **11** (2001), 337–345.

[64] I. Kingma, J.H. van Dieën, M.P. de Looze, H.M. Toussaint, P. Dolan and C.T.M. Baten, Asymmetric low back loading in asymmetric lifting movements is not prevented by pelvic twist, *Journal of Biomechanics* **31**(6) (1998), 527–534.

[65] K. Kjellberg, L. Lindbeck and M. Hagberg, *Lifting techniques and some biomechanical back variables – a study on women*, in XVIth ISB Tokyo Congress, August 25–29, 1997, hosted by the University of Tokyo: book of abstracts, Tokyo: International Society of Biomechanics, 1997, pp. 286.

[66] S.R. Krajcarski, J.R. Potvin and J. Chiang, The in vivo dynamic response of the spine to perturbations causing rapid flexion: effects of pre-load and step input magnitude, *Clinical Biomechanics* **14** (1999), 54–62.

[67] S. Kumar, Spinal compression at peak isometric and isokinetic exertions in simulated lifting in symmetric and asymmetric planes, *Clinical Biomechanics* **11**(5) (1996), 281–289.

[68] C. Larivière, D. Gagnon and P. Loisel, A biomechanical comparison of lifting techniques between subjects with and without chronic low back pain during freestyle lifting and lowering tasks, *Clinical Biomechanics* **17**(2) (2002), 89–98.

[69] S.A. Lavender, Y.C. Li, G.B. Andersson and R.N. Natarajan, The effects of the lifting speed on the peak external forward bending, lateral bending and twisting spine moments, *Ergonomics* **42**(1) (1999), 111–125.

[70] C. Leboeuf-Yde and K. Ohm Kyvik, At what age does low back pain become a common problem? A study of 29, 424 individuals aged 12–41 years, *Spine* **23**(2) (1998), 228–234.

[71] P. Lee, A. Helewa, C.H. Goldsmith, H.A. Smythe and L.W. Stitt, Low back pain: prevalence and risk factors in an industrial setting, *The Journal of Rheumatology* **28**(2) (2001), 346–351.

[72] T.P.J. Leskinen, H.R. Stalhammar, I.A.A. Kuorinka and J.D.G. Troup, Hip torque, lumbosacral compression, and intraabdominal pressure in lifting and lowering tasks, in: *Biomechanics IX-B*, D.A. Winter, ed., Champaign, IL: Human Kinetics Publishers, 1985, pp. 55–59.

[73] T.P.J. Leskinen, E. Takala and H.R. Stalhammar, Lumbar and pelvic movements when stooping and lifting, in: *Biomechanics X-A*, B. Jonsson, ed., Champaign, IL: Human Kinetics Publishers, 1987, pp. 195–199.

[74] P.K. Levangie, The association between static pelvic asymmetry and low back pain, *Spine* **24**(12) (1999), 1234–1242.

[75] W. Liemohn, L.B. Snodgrass and G.L. Sharpe, Unresolved controversies in back management – a review, *Journal of Orthopaedic & Sports Physical Therapy* **9**(7) (1988), 239–244.

[76] G.J. Macfarlane, E. Thomas, A.C. Papageorgiou, P.R. Croft, M.I.V. Jayson and A.J. Silman, Employment and physical work activities as predictors of future low back pain, *Spine* **22**(10) (1997), 1143–1149.

[77] S. MacKinnon and J.C. Li, Temporal relationships of load and lumbar spine kinematics during lifting, *International Journal of Industrial Ergonomics* **22** (1998), 359–366.

[78] P.H. Mairiaux, P.R. Davis, D.A. Stubbs and D. Baty, Relation between intra-abdominal pressure and lumbar moments when lifting weights in erect posture, *Ergonomics* **27**(8) (1984), 883–894.

[79] N. Maniadakis and A. Gray, The economic burden of back pain in the UK, *Pain* **84** (2000), 95–103.

[80] W.S. Marras and K.G. Davis, Spine loading during asymmetric lifting using one versus two hands, *Ergonomics* **41**(6) (1998), 817–834.

[81] W.S. Marras, K.G. Davis, S.A. Ferguson, B.R. Lucas and P. Gupta, Spinal loading characteristics of patients with low back pain compared with asymptomatic individuals, *Spine* **24**(23) (2001), 2566–2574.

[82] W.S. Marras, K.P. Granata and K.G. Davis, Variability in spine loading model performance, *Clinical Biomechanics* **14** (1999), 505–514.

[83] W.S. Marras, K.P. Granata, K.G. Davis, W.G. Allread and M.J. Jorgensen, Effects of box features on spine loading during warehouse order selecting, *Ergonomics* **42**(7) (1999), 980–996.

[84] W.S. Marras and C.M. Sommerich, A three-dimensional motion model of loads on the lumbar spine: I. Model structure, *Human Factors* **33**(2) (1991), 123–137.

[85] C.E. McCoy, A.G. Hadjipavlou, T. Overman, J.T. Necessary and C. Wolf, Work-related low back injuries caused by unusual circumstances, *Journal of Orthopaedic & Sports Physical Therapy* **26**(5) (1997), 260–265.

[86] S.M. McGill and R.W. Norman, Dynamically and statically determined low back moments during lifting, *Journal of Biomechanics* **18**(12) (1985), 877–885.

[87] S.M. McGill and R.W. Norman, Low back biomechanics in industry: The prevention of injury through safer lifting, in: *Current Issues in Biomechanics*, M.D. Grabiner, ed., Champaign, IL: Human Kinetics, 1993, pp. 69–120.

[88] S.M. McGill, N. Patt and R.W. Norman, Measurement of the trunk musculature of active males using CT scan radiography: Implications for force and moment generating capacity about the L4/L5 joint, *Journal of Biomechanics* **21**(4) (1988), 329–341.

[89] J.M. Morris, D.B. Lucas and B. Bresler, Role of the trunk in stability of the spine, *The Journal of Bone and Joint Surgery* **43-A**(3) (1961), 327–351.

[90] S.J. Morrissey and Y.H. Liou, Maximum acceptable weights in load carriage, *Ergonomics* **31** (1988), 217–226.

[91] National Institute for Occupational Safety and Health, *A work practices guide for manual lifting*, Cincinnati, OH: US Department of Health and Human Services, NIOSH, 1981.

[92] P.K. Nielsen, L. Andersen and K. Jorgensen, The muscular load on the lower back and shoulders due to lifting at different lifting heights and frequencies, *Applied Ergonomics* **29**(6) (1998), 445–450.

[93] M. Nordin, N. Greenidge, C. Tauber and J. Ngai, Spinal configuration during lifting, *Bulletin of the Hospital for Joint Diseases Orthopaedic Institute* **46**(1) (1986), 31–36.

[94] C.M. Norris, Biomechanics of the lumbar spine, in: *Back Stability*, C.M. Norris, ed., Champaign, IL: Human Kinetics Publishers, 2000, pp. 14–42.

[95] C.M. Norris, Stabilization mechanisms in the lumbar spine, in: *Back Stability*, C.M. Norris, ed., Champaign, IL: Human Kinetics Publishers, 2000, pp. 43–66.

[96] Occupational Safety and Health Administration, *Back injuries: Nation's number one workplace safety problem*, Available at: http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=FACT_SHEETS&p_id=146, 1993, Accessed June 25, 2002.

[97] K.S. Park and D.B. Chaffin, A biomechanical evaluation of two methods of manual load lifting, *AIIE Transactions* **6**(2) (1974), 105–113.

[98] P. Patterson, J. Congleton, R. Koppa and R.D. Huchingson, The effects of load knowledge on stresses at the lower back during lifting, *Ergonomics* **30**(3) (1987), 539–549.

[99] A. Plamondon, M. Gagnon and P. Desjardins, *Validation of a 3D segment model to estimate the net reaction forces and moments at the L5/S1 joint*, in Canadian Society for Biomechanics VIIIth biennial conference, Calgary: Canadian Society of Biomechanics, 1994, 196-197.

[100] A.L. Pool-Goudzwaard, A. Vleeming, R. Stoeckart, C.J. Snijders and J.M.A. Mens, Insufficient lumbopelvic stability: a clinical, anatomical and biomechanical approach to 'a specific' low back pain, *Manual Therapy* **3**(1) (1998), 12–20.

[101] M.H. Pope, D.G. Wilder and M.H. Krag, Biomechanics of the lumbar spine, in: *The adult spine: principles and practice*, J.W. Frymoyer, T.B. Ducker, N.M. Hadler, J.P. Kostuik, J. Weinstein and T.S. Whitecloud, eds, New York: Raven Press, Ltd., 1991, pp. 1487–1501.

[102] M.E. Robinson, P.D. O'Connor, F.R. Shirley and M. Mac Millan, Intrasubject reliability of spinal range of motion and velocity determined by video motion analysis, *Physical Therapy* **73**(9) (1993), 626–631.

[103] A. Roozbazar, Biomechanics of lifting, in: *Biomechanics IV*, R.C. Nelson and C.A. Morehouse, eds, Baltimore: University Park Press, 1974, pp. 37–43.

[104] A. Shirazi-Adl and M. Parnianpour, Load-bearing and stress analysis of the human spine under novel wrapping compression loading, *Clinical Biomechanics* **15** (2000), 718–725.

[105] A.N. Sjolie and A.E. Ljunggren, The significance of high lumbar mobility and low lumbar strength for current and future low back pain in adolescents, *Spine* **26**(23) (2001), 2629–2636.

[106] C.J. Snijders, A. Vleeming and R. Stoeckart, Transfer of lumbosacral load to iliac bones and legs: Part 2: Loading of the sacroiliac joints when lifting in a stooped posture, *Clinical Biomechanics* **8** (1993), 295–301.

[107] P.J. Sparto, M. Parnianpour, T.E. Reinsel and S. Simon, The effect of fatigue on multijoint kinematics, coordination, and postural stability during a repetitive lifting test, *Journal of Orthopaedic & Sports Physical Therapy* **25**(1) (1997), 3–12.

[108] M.S. Sullivan, Back support mechanisms during manual lifting, *Physical Therapy* **69**(1) (1989), 38–45.

[109] H.M. Toussaint, A.F. de Winter, Y. de Haas, M.P. de Looze, J.H. van Dieën and I. Kingma, Flexion relaxation during lifting: implications for torque production by muscle activity and tissue strain at the lumbo-sacral joint, *Journal of Biomechanics* **28**(2) (1995), 199–210.

[110] H.M. Toussaint, C.E. van Baar, P.P. van Langen, de M.P. Looze and J.H. van Dieën, Coordination of the leg muscles in backlift and leglift, *Journal of Biomechanics* **25**(11) (1992), 1279–1289.

[111] J.D.G. Troup, Dynamic factors in the analysis of stoop and crouch lifting methods: a methodological approach to the development of safe materials handling standards, *Orthopedic Clinics of North America* **8**(1) (1977), 201–209.

[112] J.D.G. Troup, T.P.J. Leskinen, H.R. Stalhammar and I.A.A. Kuorinka, A comparison of intra-abdominal pressure increases, hip torque, and lumbar vertebral compression in different lifting techniques, *Human Factors* **25**(5) (1983), 517–525.

[113] K. Ueno and Y.K. Liu, A three-dimensional non-linear finite model of lumbar intervertebral joint in torsion, *Journal of Biomechanical Engineering* **109** (1987), 200–209.

[114] J.C.E. van der Burg and J.H. van Dieën, The effect of timing of a perturbation on the execution of a lifting movement, *Human Movement Science* **20** (2001), 243–255.

[115] J.C.E. van der Burg, J.H. van Dieën and H.M. Toussaint, Lifting an unexpectedly heavy object: the effect on low-back loading and balance loss, *Clinical Biomechanics* **15** (2000), 469–477.

[116] J.H. van Dieën, M.J.M. Hoozemans and H.M. Toussaint, Stoop or squat: a review of biomechanical studies on lifting techniques, *Clinical Biomechanics* **14**(10) (1999), 685–696.

[117] J.H. van Dieën and I. Kingma, Total trunk muscle force and spinal compression are lower in asymmetric moments as compared to pure extension moments, *Journal of Biomechanics* **32** (1999), 681–687.

[118] Victorian WorkCover Authority, Annual Report Victorian WorkCover Authority 1999/2000, Melbourne, VIC: Victorian WorkCover Authority, 2001.

[119] E. Volinn, The epidemiology of low back pain in the rest of the world: a review of surveys in low- and middle- income countries, *Spine* **22**(15) (1997), 1747–1754.

[120] G. Waddell, Low back pain: a twentieth century health care enigma, *Spine* **21**(24) (1996), 2820–2825.

[121] T.R. Waters, S.L. Baron and K. Kemmlert, Accuracy of measurements for the revised NIOSH lifting equation, *Applied Ergonomics* **29**(6) (1998), 433–438.

[122] T.R. Waters, V. Putz-Anderson and S.L. Baron, Methods for assessing the physical demands of manual lifting: A review and case study from warehousing, *American Industrial Hygiene Association Journal* **59** (1998), 871–881.

[123] T.R. Waters, V. Putz-Anderson and A. Garg, *Applications manual for the revised NIOSH lifting equation*, Cincinnati, OH: US Department of Health and Human Services, NIOSH, 1994.

[124] WorkCover Corporation of South Australia, *Lifting and carrying: The cost*, Available at: http://www.workcover.com/training/liftCost.html, 2002, Accessed March 3, 2002.