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Review

Tolerance of the lumbar spine to shear: A review and recommended exposure limits

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ABSTRACT

Background: The lumbar spine may experience significant shear forces during occupational tasks due to the force of gravity acting on the upper body when bending the trunk forward, or when performing tasks involving pushing or pulling. Shear force limits of 1000 N and 500 N have been recommended by previous authors for maximum permissible limit and action limit, respectively.

Methods: The present paper reviews literature in terms of shear tolerance (ultimate shear stress and fatigue life in shear stress) of the lumbar spine and develops recommended limits based on results of studies examining shear loading of human motion segments. Weibull analysis was used to assess fatigue failure data to estimate distributions of failure at different percentages of ultimate shear stress.

Findings: Based on Weibull analysis of fatigue failure data from the best available data, a 1000 N shear limit would appear acceptable for occasional exposure to shear loading ($\leq$100 loadings/day); however, a 700 N limit would appear appropriate for repetitive shear loading (100–1000 loadings/day) for most workers.

Interpretation: Results of the current analysis support the 1000 N limit for shear stress, but for a rather limited number of cycles (<100 per day). Due to the logarithmic nature of the fatigue failure curve, a 700 N shear limit would appear to be acceptable for frequent shear loadings (100–1000 per day). This value is slightly higher than the action limit of 500 N previously recommended.

1. Introduction

The lumbar spine is subjected to a multitude of loading combinations in everyday life, both on and off the job. Loading modalities on the spine are frequently categorized as compressive forces (forces acting down the long axis of the spine), shear forces (forces acting at 90° from the compressive forces defined above, in both lateral and anterior–posterior [A–P] directions) and torsional forces (rotation forces acting around the long axis of the spine). While these are convenient classifications, in reality, the spine is subjected to combinations of these loading modes on a nearly continual basis.

Of the three predominant loading classifications, spinal compression is unquestionably the most studied and the best understood (Adams et al., 2006; Bogduk, 1997). Studies have indicated, for example, that lifting heavy or bulky objects in a rapid fashion can lead to compressive forces sufficient to lead to damage of spinal structures. The most likely cause of damage is fatigue failure (Brinckmann et al., 1988; Gallagher et al., 2005); however, on occasion the spine's ultimate compressive strength may be exceeded. The vertebral endplate appears to be a common site of injury; however, disks, zygapophyseal joints, and other structures may incur damage resulting from compressive loading as well (Bogduk, 1997).

While compressive forces clearly have the largest magnitude compared to the other classifications under normal circumstances, shear forces may also be substantial. Shear forces (specifically in the A–P direction) often occur due to the force of gravity acting on the upper body when bending the trunk forward, but can also be quite significant in occupational tasks such as pushing and pulling (Knapik and Marras, 2009). The forces associated with shear may be lower than those associated with compression; however, the spinal structures loaded in shear are also weaker, and may be similarly vulnerable to damage given large or repeated shear loading. The zygapophyseal joints appear to be structures developed to resist shear loading as well as axial loading. If these structures are absent, the disk simply continues to give way when subjected to shear loading. For this reason it appears likely the large majority of shear forces experienced by the spine are resisted by structures of the neural arch, especially when the vertebral bodies are loaded in pure shear (Adams et al., 2006). However, different postural configurations of the vertebrae and exposure to complex loading patterns may affect the capacity of the neural arch to withstand shear forces.

2. Shear forces on the lumbar spine

2.1. Definition of shear

In the current context, we define a shear force as a force that acts parallel to the mid-plane of the disk of a specified motion segment of

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interest (Adams et al., 2006). In pushing and pulling tasks, shear in the anterior–posterior direction is of primary interest; however, significant lateral shear forces may also be present in pushing and pulling tasks. The current discussion will focus on A–P shear, as shear forces in these directions would be expected to be predominant.

2.2. Spinal tissues providing shear resistance

Different structures are thought to be involved in support of anterior versus posterior shear loading. The neural arch (especially the pars interarticularis) and intervertebral disk appear to support anterior shear forces, while the interspinous ligaments, capsular ligaments and annulus fibrosis of the disk appear to support posterior shear (Yingling and McGill, 1999b). The neural arch is thought to be the primary structure providing resistance to anterior shear in the spine (Adams et al., 2006). The shape of the neural arch changes from L5–S1 to L1–L2 and may negatively influence the ability to resist shear at the upper levels. The collagen fibers in the intervertebral disks themselves are poorly oriented to resist shear. If the zygapophyseal joints are removed and the motion segment is subjected to shear loading, the segment will creep to twice the degree compared to that possible with intact zygapophyseal joints (Cyron and Hutton, 1981). More than 20 mm creep possible in severe shear loading with removed zygapophyseal joints, and greater creep are typically seen with more degenerated disks (Cyron and Hutton, 1981).

Younger spines (<30 yrs) may be more susceptible to shear forces due to more elastic disks and incomplete ossification of the neural arch (Cyron and Hutton, 1978). However, the loss of bone mineral content with old age may also lead to an increased propensity for zygapophyseal joint failure. The orientation of the erectors spinae (esp. the multifidus) help these muscles resist anterior shear; however, in an upright posture the muscles of the trunk may cause a net anterior shear force to be experienced by the lumbar spine (Adams et al., 2006).

2.3. Spinal structures failing in shear

Shear loading of the pars interarticularis indicates that this structure can resist approximately 2 kN when subjected to a single load to ultimate stress (Adams et al., 2006). Fracture typically occurs to the pars or the pedicle when loaded in shear. Fractures of this sort are often seen in spondylolysis, and shear loading of the spine may be a possible factor in the development of this disorder. Capsule tears and laxity are also likely consequences of shear loading (Beadon et al., 2008; Yingling and McGill, 1999a,b). A cadaver study on human spines indicated that shear forces are associated with certain patterns of endplate fracture, with increased shear associated with the development of a stellate fracture pattern (Gallagher et al., 2006). Lower shear forces tended to result in a depression of the endplate without fracture.

3. Shear tolerance of spinal tissues

There appear to be a limited number of studies specifically examining shear tolerance of the human lumbar spine, much of which is older, and which have a somewhat limited number of female specimens. A database on shear loading and tolerance maintained by one of the authors (WSM) was consulted which contained 27 references on shear tolerance of either human or porcine lumbar spines and/or biomechanical modeling estimates of shear load on the human lumbar spine. Searches of the PubMed database resulted in 6 and 7 papers to queries "shear fatigue failure spine" and "lumbar spine shear tolerance", respectively, most of which were already contained in the database. However, based on these searches, and examination of reference lists of articles in the database, 2 additional relevant articles were added.

3.1. Human studies

3.1.1. Ultimate shear stress

Fig. 1 provides a summary of the results of tests of ultimate shear strength of human cadaveric lumbar spines by various authors. Cyron et al. (1976) in a study of ultimate shear stress of inferior facet joints tested 44 human cadaver vertebrae aged 26–75. These authors found that the range of applied loads resulting in failure was 0.6–2.8 kN, with failure occurring in either the pars or the pedicle. These fractures resembled damage often seen in spondylolysis.

Begeman et al. (1994) tested a working age cohort of cadaver specimens at load rates of 0.5 mm/s and 50 mm/s, and found that cadaver anterior lumbar failure started at 1200 N and hard tissue failure occurred at the 2800 N level. Frei et al. (2002) tested 6 human cadaveric motion segments (T12 − L1) and tested them at a load rate of 0.5 mm/s to failure and found an average shear failure load of 2240 N (± 570 N SD) with a range of 1400–3200 N. Bisschop et al. (2012) tested the ultimate shear stress of freshly frozen (−20 °C) human cadavers (mean age 72.1 years, range 53–89 years). Before testing, bone mineral content (BMC, in grams) was measured for each lumbar spinal section (L1–L4) and magnetic resonance imaging (MRI) was used to grade disk degeneration of the motion segments employed. Segments were loaded with an axial compressive force of 1600 N. Subsequently, anterior shear load was applied with a constant rate of 2.0 mm/min on the casting mold containing the cranial vertebral body, until failure of the vertebral motion segment.

3.1.2. Fatigue failure

Few studies have looked at the effects of repetitive shear loading on the failure of spinal motion segments. Cyron and Hutton (1978) subjected the inferior articular facets of 74 cadaveric lumbar vertebrae (aged 14–80) to cyclical shear loading of 380–760 N for up to 400,000 cycles or until failure. The range of the shear loads applied was fairly low compared to the ultimate shear stress limits observed in previous studies, and unsurprisingly the vertebrae were generally able to withstand tens or hundreds of thousands of cycles. Only a few working age specimens (9 out of 50) lasted less than 10,000 cycles, and only three out of fifty lasted less than 1500 cycles. More recently, Patwardhan et al. (2002) induced a high Grade 1 listhesis in

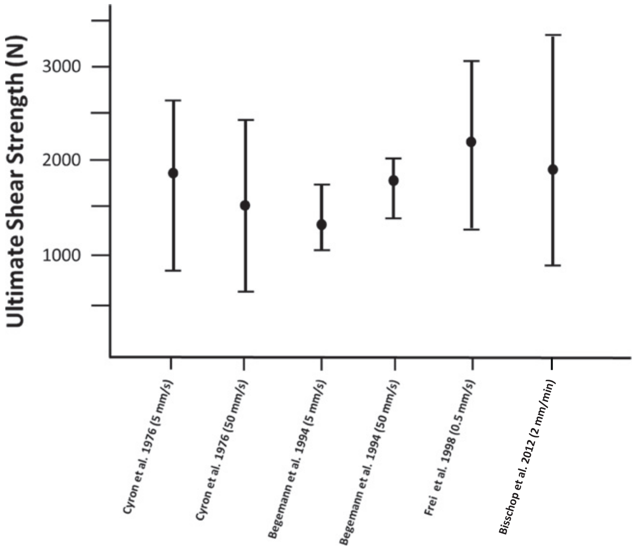

Fig. 1. Summary of studies examining the ultimate shear stress of human lumbar motion segments (error bars represent the range of shear tolerance values observed in these studies).

human ex vivo specimens using a cyclic shear model. In this study, 24% slip was observed at shear loads of greater than 1200 N. When loading was removed, this slip was decreased to 17%.

3.2. Porcine studies

Several investigators have used porcine models to investigate shear tolerance of spinal motion segments. Such studies can have substantial value in terms of understanding the biomechanical properties of spinal columns, especially in terms of loading relationships and their effects on spinal tissues. However, it must also be kept in mind that differences exist in size and shape of porcine spines as opposed to human spines. For example, the cross-sectional area of porcine spines is only about 60% that of human spines. Nevertheless, some have found that porcine specimens possess similar load tolerance values to humans, including shear tolerance (McGill et al., 1998; Yingling and McGill, 1999a).

3.2.1. Ultimate shear stress

Yingling and McGill (1999b) examined the failure mechanics of porcine cervical spine motion segments (C3–C4 and C5–C6) under posterior shear loads at load rates of 100 N/s or 10,810 N/s in a flexed or neutral posture tested to failure. The average ultimate load at failure was 2065 N for whole specimens, and slightly (but not significantly) less for specimens without ligaments (1955 N). Sectioning of the facet joints decreased average shear tolerance to 1537 N. Predominant injuries from posterior shear loading were avulsions of the endplates.

3.3. Fatigue failure

Beadon et al. (2008) used a porcine model to produce a biomechanical model of spondylolysis and spondylolisthesis using an accelerated cyclic loading regimen. Five fresh functional spinal units (three L6–S1 and two L4–L5) were subjected to cyclic loading (300–600 N for 7200 cycles at 2 Hz), then a combination of the same cyclic load plus a sudden impulse loading (1500 N every 1200 cycles) until a slippage of 15% was achieved. A subsequent elevated cyclic loading regimen was performed, with cyclic loads of 500–800 N until a slippage of 25% was achieved. Specimens did not show any significant slip in the initial cyclic loading period, however, the addition of the impulse loads in the second phase cause significant slippage (25.2%) and pars fractures by completion of the fourth impulse load (7200–9720 cycles). The subsequent elevated cyclic loading protocol led to a grade II spondylolisthesis after a mean of 14,660 (±7566 SD) cycles.

4. Shear exposure limits

4.1. Previous recommendations

A couple of authors have suggested exposure limits to spinal shear forces. McGill et al. (1998) recommended a maximum permissible limit (MPL); representing an unacceptably high risk of injury, of 1000 N of lumbar spine shear force for single exertions. These authors in conjunction with others (Norman et al., 1998) suggested an action limit (AL), representing an unacceptable risk to most workers without engineering or administrative controls, of 500 N. The 1000 N limit for exposure to shear was echoed by the NRC/IOM Report (NRC-IOM, 2001), citing studies by Adams et al. (1994) and Miller et al. (1986) for intact spinal segments (Table 5.1 on page 191).

4.2. Critique of previous shear exposure limit recommendations

One significant drawback of the recommended exposure limits noted above is that there is no sensitivity given to the frequency of loading. Studies have made it abundantly clear that biological tissues experience damage as the result of fatigue failure (Gallagher and Heberger, 2012), and that the amount of force that can be tolerated for multiple exposures is lower than that which can be tolerated for occasional ones. Fatigue failure studies of the lumbar spine in compression (Brinckmann et al., 1988; Gallagher et al., 2005) and the extensor digitorum longus in tension (Schechtman and Bader, 1997) have indicated that loadings below 40% ultimate stress (US) can generally be withstood for thousands of loading cycles, while loadings of 60% US can be tolerated by a vast majority of specimens for a hundred cycles but will fail much more rapidly if additional loading cycles are imposed. The limit of 40% US seems reasonable as the fatigue limit for most materials is 30% US (this is the limit at which most materials can sustain indefinite loading cycles). The ability of biological tissues to repair themselves would seem to support a limit somewhat higher than the endurance limit as a design limit (Nash, 1966). While some authors have argued that data from porcine studies provide similar results to those of human specimens (Yingling and McGill, 1999a,b), due to the cube-square law, it would seem most appropriate to base exposure limits for humans on studies of shear stress examining failure properties on human specimens. In addition, the lower action limit of 500 N recommended previously may be unnecessarily restrictive due to the logarithmic nature of fatigue failure of human tissues.

5. Rationale for developing shear limits

5.1. Weibull analyses of fatigue failure data for lumbar spine shear loading

Weibull analysis is a method for modeling data sets containing values greater than zero, such as fatigue failure data (Nelson, 1982). The primary advantage of Weibull analysis is the ability to provide reasonably accurate failure analysis and failure forecasts with small samples, as are often present in fatigue failure tests of cadaveric specimens. Another advantage of Weibull analysis is that it provides a simple and useful graphical plot of the failure data. The Weibull data plot (an example can be found in Fig. 2) can be particularly informative. The horizontal scale is a measure of the number of cycles experienced using a log scale. The vertical scale represents the cumulative percentage of failures. The two defining parameters of the Weibull line are the shape parameter (β) represented by the slope of the regression line, and the "characteristic life" or scale parameter (α), which represents the number of cycles at which 63.2% of specimens would be expected to fail. The characteristic life is a common

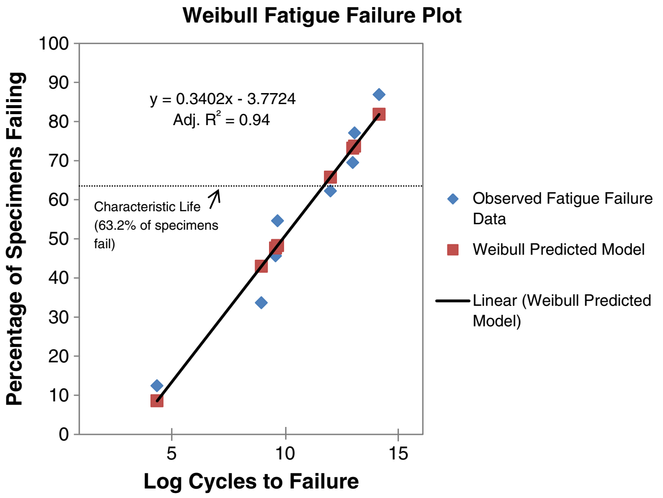

Fig. 2. Example of Weibull analysis of fatigue failure data of human lumbar specimens subjected to shear loading. Note that the regression slope represents the Weibull shape parameter (β), and the Characteristic Life represents the Weibull scale parameter (α).

"time to failure" measure in Weibull analysis, and is equivalent to the mean time to failure when the shape parameter (β) is equal to one.

The Weibull distribution parameters from a set of fatigue failure data are typically obtained using the steps described below. The present analysis was performed using Excel software. The following steps were taken, as described by Stone (2012):

1. The fatigue data was ordered from shortest life to longest.
2. A regression analysis was conducted to calculate the median rank for each life value (Nelson, 1982). (The regression technique may vary based on sample size, type of data, etc.) The median rank is a value between zero and one and approximately represents the expected fraction of the distribution expected to exist below each specimen's observed number of cycles to failure.
3. The double logarithm 1 / (1 − median rank) was plotted vs. the logarithm of the actual life data. The data points typically fall very near a straight line.
4. A best-fit line was established for the set of data points.

Our approach was to derive shear exposure limits based on analyses of available shear fatigue failure tolerance from human lumbar spine specimens. Specifically, it was considered important to evaluate limits based on fatigue failure studies due to the repeated loading often experienced by workers in occupational settings. Further, it was recognized that a single criterion value for recommended shear force was not adequate, since both theory and evidence indicate that loads tolerable to human tissues for repeated exposure will be lower than those that can be tolerated for occasional exposure (Brinckmann et al., 1988; Gallagher et al., 2005, 2006; Schechtman and Bader, 1997).

Given the scarcity of fatigue failure data involving shear loading, the current Weibull analysis employed a combination of data sets. The first data set involved tests of ultimate strength in shear loading (Cyron et al., 1976). Data from this experiment were subjected to a regression analysis by the current authors to evaluate the role of factors such as the load rate, level of the lumbar specimen, and load rate. The following regression equation was obtained:

$$\text{Force (N)} = 577.3 + 170.2 * \text{Level} + 847.6 * \text{Gender} - 63.5 * \text{Load rate (cm/s)} \quad (1)$$

where:

Level level of the lumbar spine (1–5 representing lumbar levels L1–L5)
Gender specimen gender where 0 = female and 1 = male
Load rate load rate in cm/s.

The adjusted R^2 for the equation was 0.64. Results of this regression analysis indicate that increasing shear forces can be progressively tolerated at the lower levels of the spine, and that increasing load rate will decrease shear tolerance. A rather large difference in gender response is also indicated by this regression equation.

The regression equation derived from the Cyron et al. (1976) data was used to estimate the ultimate shear strength (USS) of working age (18–65 years) cadaveric specimens tested to failure via fatigue loading in the study reported by Cyron and Hutton (1978). This permitted Weibull analyses to be performed on the fatigue failure data of Cyron and Hutton (1978). These analyses estimated the failure distributions from which the specimens were derived for specimens stressed at levels ranging from 30% to 70% USS. Results of these analyses are shown in Fig. 3. As can be seen in this figure, specimens loaded at 30–40% USS have the longest fatigue life, followed by specimens loaded at 40–50% USS and 50–60% USS (with very similar fatigue life curves), while specimens loaded at 60–70% show a more dramatic decline in fatigue life.

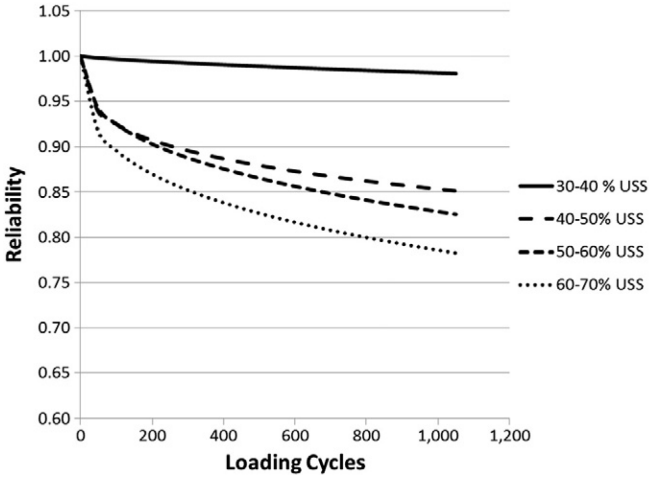

Fig. 3. Predicted reliability (number of cycles to failure) for human lumbar specimens exposed to loading at various percentages of estimated ultimate shear strength based on Weibull analysis of data from Cyron and Hutton (1978).

In an ideal world, it would be feasible to develop standards that would protect even the weakest individual from injury. However, due to the wide variability of tissue tolerance, developing standards to protect everyone would result in loading values that are unnecessarily protective for the vast majority of individuals. Thus, in developing standards or recommendations to control MSDs, it is necessary to strike a balance where most (but not all) individuals will be reasonably protected. Such an approach has been used in setting psychophysically-based standards (Snook et al., 1978) and the National Institute for Occupational Safety and Health revised Lifting Equation (Waters et al., 1993), for example. For the current analysis, we propose a value of shear loading that will be protective against damage for 90% of individuals.

Using the 90% criterion the number of loading cycles that can be tolerated for loadings of 30–40% US would be 10,400 cycles. Loadings of 40–50%, 50–60% and 60–70% US would 261, 218, and 88, respectively. Given that the average ultimate shear stress withstood by spinal segments was 1901 N for males and 1731 N for females (Cyron et al. 1976), a reasonable value for highly repetitive (>100 loadings/day) shear loading would be 760 N for males and 692 N for females (i.e., 40% ultimate shear stress). For infrequent loading (≤100 loadings/day), a 60% ultimate shear stress value would be expected to be tolerable for the vast majority of working age individuals. This would correspond to loadings of 1140 N for males and 1038 N for females. Thus, these data would seem to support a 1000 N limit for exposure for relatively infrequent shear loading. However, a reduced limit of 700 N would be recommended for more frequent exposure to shear loadings (100–1000 loadings/day). Shear loadings of less than 700 N (<30% USS) would be expected to result in minimal risk even with highly repetitive activities, except for the very weakest spines. Loadings greater than 60% US would lead to damage in very small number of cycles and should be avoided.

5.2. Assessment of recommended shear limits from available data

Comparisons of these recommended values to data from available studies seem to provide support for these levels. For example, the Cyron and Hutton (1978) fatigue failure study loaded spines to 760 N of shear for several hundred thousand cycles and found that only 6% of working age specimens failed to last at least 1500 cycles. This result suggests that the vast majority of workers would be protected by a 700 N shear limit for frequent exposure. Repeated exposure to shear loads of 1200 N by Patwardhan et al. (2002) led to a

Grade 1 listhesis, suggesting that such a load is excessive for repeated shear exposures.

6. Discussion

The current paper examines the literature on shear tolerance of spinal motion segments to determine appropriate limits for shear exposure for improved job design to reduce the risk of low back pain. Based on analysis of available data, it was determined that limits of 1000 N be recommended for occasional exposure to shear (<100 loadings/day), and that a 700 N limit be recommended for frequent exposure to shear (100–1000 loadings per day). Based on Weibull analysis of fatigue failure data for shear, these values would be protective for 90% of working age lumbar spines.

The recommendations developed in this paper are based on data that are limited in several respects. One limitation of the available data is the generally poor representation of female specimens in current studies. Another limitation of the available data is that fatigue failure studies in humans are also scarce and the studies performed thus far have not adequately described the fatigue failure relationship. One of the largest studies on fatigue failure is that by Cyron and Hutton (1978), which used a loading regimen that may have been below the endurance limit of most of the specimens examined, meaning most segments would not be expected to fatigue fail, even after extensive testing. The Patwardhan et al. (2002) study used a loading regimen (1200 N) higher than the often cited 1000 N value for occasional shear exposure. Furthermore, it should be recognized that the data upon which these recommendations are based are based upon direct loading or the neural arch in pure shear, and that different load tolerances would be expected when examining complex loading conditions or testing of motion segments in flexed as opposed to neutral posture. However, the authors feel that these data represent the best data currently available to evaluate shear tolerance of human lumbar spines.

It should also be noted that shear tolerance studies have varied considerably in terms of methodology, involving the loading of different vertebral or functional spinal unit (FSU) structures, for example, making comparisons difficult. Furthermore, many studies have employed porcine specimens, and it is not clear how similar porcine specimen tolerance to shear compares to human specimens, although several studies have found shear tolerances to be in the same general range (McGill et al., 1998; Yingling and McGill, 1999a,b).

The current recommendations agree in part with the 1000 N level as a limit for shear for occasional exposure, as suggested previously by McGill et al. (1998) for their MPL, and as suggested by the NRC-IOM (2001). However, the 700 N value for repeated stress which is based upon fatigue failure models is somewhat higher than the 500 N proposed as an action limit by McGill et al. (1998). Data from shear studies indicate that 760 N of shear appears to be well tolerated even for an extended number of testing cycles (Cyron and Hutton, 1978); therefore, 500 N appears to be excessively restrictive. It should be noted in this regard that the fatigue failure curve is logarithmic in nature; thus, relatively small decreases in stress on the tissues can lead to substantial increases in fatigue life at lower force levels (Schechtman and Bader, 1997).

Our knowledge of the mechanical properties of human tissues is derived primarily from experiments on animals and human cadaveric tissue and it is necessary to address the limitations of these techniques. One clear limitation associated with the use of cadaveric material, particularly in fatigue failure experiments, is that during life, biological tissues have the capacity for self-healing (Nash, 1966). This capacity is lost in the non-physiologic state. There may also be certain changes in cadaveric tissues after death, including those resulting from changes in temperature, which may reduce the extensibility of tendons and ligaments, and which reduce the rate of creep slightly. In addition, in motion segment tests, dissection can weaken the longitudinal and supraspinous ligaments because they have fibers that span several vertebrae, which may reduce resistance of the segments to bending forces slightly (Adams et al., 2006).

The recommendations for shear loading presented here are for situations where shear force is of utmost concern in terms of injury risk, for example pushing and pulling tasks. There are certainly cases where compressive forces will be the main concern. Of course, many occupational tasks involve both high compression and high shear loads on the spine. Unfortunately, the interaction of shear and compressive loads and spine tolerance is poorly understood at the present time. Future research activity will be necessary in this area.

7. Conclusions

Based on our review and evaluation of currently available shear tolerance data, the following conclusions are drawn:

1. The lumbar spine will experience significant shear forces during the performance of certain lifting activities and during pushing and pulling activities.
2. The number of studies examining shear tolerance of human lumbar spines is small and the number of female samples in these studies is somewhat limited. Studies of fatigue failure due to shear are extremely rare.
3. The ultimate shear strength (USS) of human lumbar specimens ranges from 0.6 to 3.2 kN. Average USS values for working age males and females were 1.9 and 1.7 kN, respectively.
4. Weibull analyses of fatigue failure from the data of Cyron and Hutton (1978) indicate that loadings ranging from 30 to 40% USS could be withstood for well over 1000 cycles, while loadings from 40 to 60% USS could only be withstood for 100 cycles in 90% of specimens. Loadings above 60% USS would cause more rapid damage and should be avoided.
5. Based on these analyses and data on USS of human lumbar spines, it would appear that shear loads of 1000 N would be acceptable for 90% of the working age population for infrequent loading (≤100 loadings/day), while shear loads of 700 N would be tolerable for up to 1000 loadings/day.

Conflict of interest statement

The authors are not aware of any conflicts of interest related to the present manuscript.

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