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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 (≤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

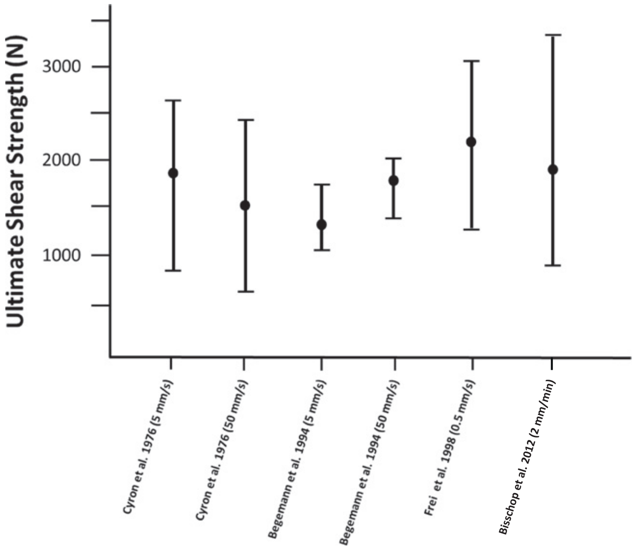

Fig. 1. Summary of studies examining the ultimate shear stress of human lumbar motion segments (error bars represent the range of shear tolerance values observed in these studies).