Biomechanics of the posterior lumbar articulating elements

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✓The clinical success of lumbar spinal fusion varies considerably, depending on techniques and indications. Although spinal fusion generally helps to eliminate certain types of pain, it may also decrease function by limiting patient mobility. Furthermore, spinal fusion may increase stresses on adjacent nonfused motion segments, accelerating the natural degeneration process at adjacent discs. Additionally, pseudarthrosis, that is, incomplete or ineffective fusion, may result in an absence of pain relief. Finally, the recuperation time after a fusion procedure can be lengthy.

The era of disc replacement is in its third decade, and this procedure has demonstrated promise in relieving back pain through preservation of motion. Total joint replacement with facet arthroplasty of the lumbar spine is a new concept in the field of spinal surgery. The devices used are intended to replace either the entire functional spinal unit (FSU) or just the facets. These devices provide dynamic stabilization for the functional spinal segment as an adjunct to disc replacement or laminectomy and facetectomy performed for neural decompression. The major role of facet replacement is to augment the instabilities created by the surgical decompression or to address chronic instability. Additionally, facet joint replacement devices can be used to replace the painful facet joints, restore stability, and/or to salvage a failed disc or nucleus prosthesis without losing motion.

In this paper the authors review and discuss the role of the lumbar facet joints as part of the three-joint complex and discuss their role in intersegmental motion load transfer and multidirectional flexibility in a lumbar FSU.

KEY WORDS • facet replacement • facet arthroplasty • posterior column biomechanics • biomechanical study

Fusion has been applied to many types of human joints for various pathological conditions, the primary rationale being relief from pain, although correction of deformity and restoration of normal force transmission may also be motivating factors.[20] In contrast with other joints, a spinal segment may be surgically treated for many reasons, including some that directly involve the posterior osseous elements, such as degenerative spondylolisthesis, osteoarthritis, ankylosing spondylolysis, or traumatic injury. Damaged posterior elements may result in misalignment, failure to articulate, or a general inability to support axial, torsional, or shear forces. Loads on the facet joints of the lumbar spine may play a major role in low-back pain, which may limit mobility and function.[3,15,28] Damaged posterior elements may also cause hypermobility or disfigurement.

Currently there is no optimum intervention procedure for facet joint disorders. Facetectomy may provide relief, but the resultant instability generally requires spinal fusion. This type of operation, however, may cause increased stress and hypermobility at the adjacent motion segments over a 5- to 10-year period after surgery.[16,19,20] As an alternative to fusion, initial attempts have focused on restoring the functional properties of the spinal segment through the use of artificial discs, but these devices alone do not fully address the mechanics of motion in the spinal column.[2,8,17,22,27]

Basic understanding of prosthetic spinal joint replacement is primarily derived from experiences with joint arthroplasty dating back to the early 1960s, when Sir J. Charnley developed the first low-friction total hip replacement.[7] Total joint replacement has revolutionized the treatment of limb arthritis, and it has been proposed that spine surgeons use the same principles in the treatment of facet disorders by replicating, to some degree, the function of the posterior elements with implantable devices.

Clinical Biomechanics of the Facet Joints

Damage to the facet joints often triggers a remodeling process in the facet bone and ligamentous capsule. This process may stabilize the joint, but it may also lead to nerve compression. In other instances, injury may lead to misaligned anatomy and a corresponding loss of mobility. Therefore, in addition to the disc, the facet joints can be considered another source of spinal disorders and debilitating pain.

As with all of the articular synovial joints, arthritis and degeneration can damage the facet's articular cartilaginous surfaces, causing pain or enlarging the articular surface, which can lead to stenosis. Osteoarthritis of the facet joint may in some cases lead to synovial cysts and subsequent back pain unrelated to disc degeneration.[9] Apart

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Abbreviations used in this paper: FSU = functional spinal unit; ROM = range of motion; TFAS = Total Facet Arthroplasty System.

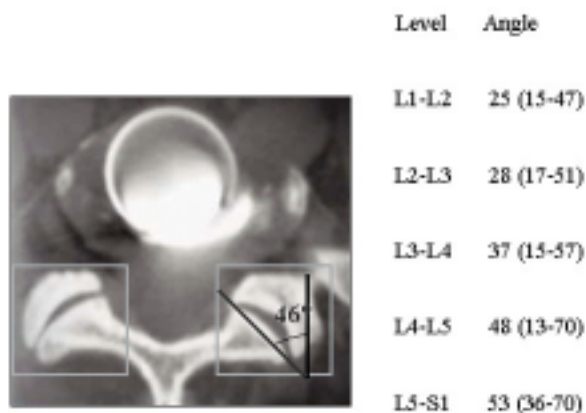| Level	Angle
L1-L2	25 (15-47)
L2-L3	28 (17-51)
L3-L4	37 (15-57)
L4-L5	48 (13-70)
L5-S1	53 (36-70)

FIG. 1. Representative neuroimage and chart showing that the facet joint angle in the transverse plane changes from a mean of 25° for L1–2 to 53° for L5– S1 (range given in parentheses).

FIG. 2. Drawing illustrating the strength of the neural arch and the origin of spondylolysis.

from these cases, however, the hypothesis that disc degeneration precedes facet joint osteoarthritis is generally accepted,[11,12,38] although there are conflicting reports,[39] and the speed and degree of degeneration can be key factors.

For a fundamental understanding of its clinical biomechanics, one must first consider the spine as a system, with interdependent components distributing loads and guiding movements. The FSU involves, in addition to the intervertebral disc, a hyperrigid system comprising the posterior facet joints, which are constrained in shear and whcih share torsional loads with the disc, and a hyporigid system comprising the posterior musculoligamentous system, which is constrained in tension, and controls shear forces together with the disc and posterior facet joints.[21]

Loads on the facet joints of the lumbar spine may play a major role in low-back pain. Shear forces resulting from axial rotation and flexion–extension motions (compressive shear loads) in an FSU are mainly transmitted through the facet joints. Although traumatic or transient shear forces will be resisted by both the disc and the facets, the disc's viscoelasticity causes slowly applied or constant shear loads to pass through the facet joints.

Assuming that form follows function, a study of the anatomy of the lumbar facet joints demonstrates a significant role in shear load–carrying capacity. Not only do the surface areas of the superior and inferior facet joints increase from L-1 to S-1,[30] as would be expected on account of the greater shear loads in the lower than in the upper spine, the facet joint angle in the transverse plane also changes, from a mean of 25° for L1–2 to 53° for L5–S1 (Fig. 1). This obliquity provides greater efficiency in shear load resistance. In contrast, the association between facet shape and degree of spinal rotation in various planes is not well defined.[4,36] For example, although the articular facets accommodate a translatory motion during sagittal plane movement, the amount of this movement is partially dependent on facet size as well as the facet capsule.[26,29,37] In comparison, Fujiwara et al.[11] found a correlation between facet sagittal orientation and osteoarthritis, but they could not determine if a predisposed orientation caused degeneration or if the orientation was induced through aggressive bone remodeling.

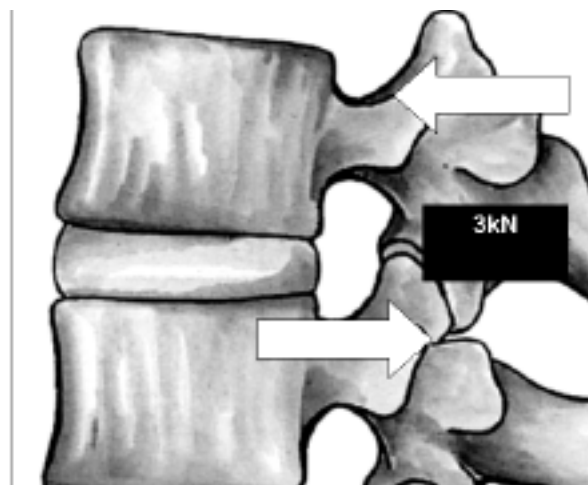Results of biomechanical studies support the shear load–carrying capacity of the facet joints. Lamy et al.[18] demonstrated facet shear load–carrying capacities of 3000 N through the facets of lumbar vertebral bodies, with failure occurring through the pedicle or the pars interarticularis (Fig. 2). Lu et al.[25] found the shear stiffness of the intact segments to be significantly higher in anterior than in posterior shear. Furthermore, they reported that the anterior column's contribution to anterior and posterior shear stiffness is only 22.8 and 23.9%, respectively. A much larger contribution was related to the posterior column, with 77.7% in anterior shear and 79% in posterior shear stiffness. After removal of the anterior column, they reported an increase in the anterior/posterior translation of 12 and 18%, respectively, whereas a drastic increase in the anterior/posterior translation (101.7 and 117.1%) occurred after posterior elements were sectioned. They concluded that the posterior elements of the lumbar spine are more efficient in resisting anterior and posterior shear loads. However, the anterior column will exhibit similar load-displacement characteristics if it is subject to greater deformations beyond the physiological range.

In addition to the bone structure of the facet joints, the facet joint capsule is one of the structures in the lumbar spine that limits motions of the vertebrae during global spine loading. It too is viscoelastic and may creep, resulting in greater segmental mobility.[23] The capsule is innervated with mechanically sensitive neurons and is a known source of low-back pain.[1,5,32,34,35,40] It has been suggested that the mechanoreceptors in the facet joint capsule could function in a manner similar to that of other joint capsules,[31] although Cavanaugh et al.[6] have suggested that only acute pain (lasting up to 7 days) and subacute pain (up to 3 months) seem related to capsule damage, and chronic pain is probably related to osteoarthritis, with involvement of substance P.[40]

Biomechanical studies have illustrated that although the diarthrodial facet joints provide both sliding articulation and transfer of compression and shear loads, the facet joint capsule transfers tension. The facet's articular surfaces come into contact in extension, limiting rotation and increasing the compressive load, and eventually contact
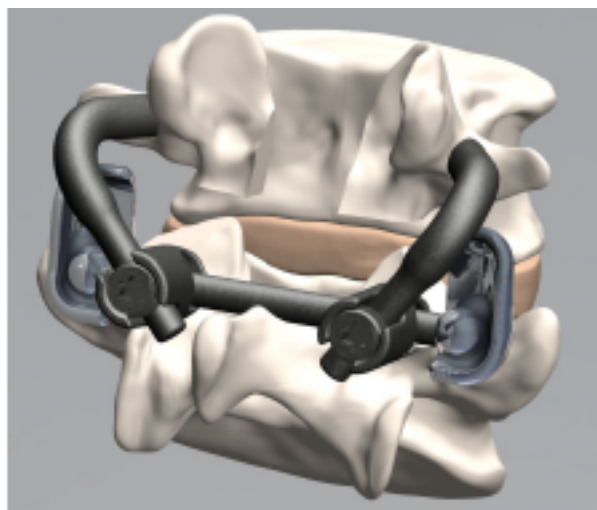
Fig. 3. Three-dimensional reconstruction of the Archus TFAS implanted in a model spine. (Reprinted with permission from Archus Orthopedics, Inc, Redmond, WA.)

Fig. 4. Bar graph showing ROM of the L4–5 segment. The *stars* indicate significant differences (p < 0.05).

unilaterally in axial rotation. In flexion, the joint opens and the facet joint capsule, in conjunction with the posterior ligamentous structures, are stretched, providing a stable, limited movement. Several biomechanical in vitro studies have demonstrated the contribution of the capsule and surrounding ligaments to total motion segment stiffness in flexion.[13,24,41] Replacing the articular surface may relieve pain, but does not fully restore joint functionality. Accordingly, the need to stabilize the facet joint in tension might be essential.

Attempts at addressing pain arising from the facet joints primarily involve injections of anesthetic agents,[33] but a review of the literature by Dreyer and Dreyfuss[10] shows that significant difficulties are encountered in identifying candidate patients. This is to be expected because the morphological characteristics likely to be associated with facet pain include disc degeneration, which is associated with root compression. Facet replacement devices are generally not intended to address pain originating at the facet joint, but instead to supply additional stability when used in conjunction with facetectomy.

Evaluation of Facet Arthroplasty Devices

Recently, Zhu et al.[42] compared the multidirectional flexibility properties and the center of intervertebral rotation of the TFAS implant by using a human cadaveric model.

The Archus TFAS is a nonfusion spinal implant indicated for treatment of patients with moderate to severe spinal stenosis. The TFAS replaces the diseased facets (and laminae, if necessary to attain adequate decompression) after surgical removal. The TFAS implant offers an alternative to rigid spinal fusion fixation, enabling intervertebral motion and restoration of stability and sagittal balance to the spine (Fig 3).

Flexibility tests were performed on each specimen in the intact and injured states and following implantation of the TFAS. The injury consisted of sectioning all posterior ligaments and facet joints at the L4–5 level, and the L-4
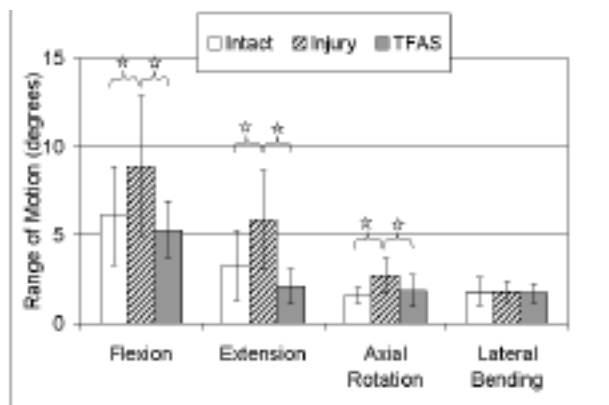
laminae and spinous process. A pure moment of ± 10 Nm was applied to the specimen with a compressive follower preload of 600 N in flexion–extension, axial rotation, and lateral bending. The position of each vertebra was monitored using the Optotrak system (Northern Digital, Inc. [NDI]). The ROM and neutral zone were calculated for the L4–5 segment. Statistical significance was determined using repeated-measures analysis of variance with probability values of less than 0.05. Zhu et al.[42] reported that the TFAS system exhibited behavior similar to the intact spine (Fig. 4).

There was no significant difference in ROM between the TFAS and the intact status in flexion, extension, lateral bending, and axial rotation. There were significant differences in ROM between the intact and the injured spines, and the injured and the TFAS in flexion, extension, and axial rotation. Compared with the intact specimen, the neutral zone with the TFAS changed little in flexion–extension and lateral bending but increased significantly in axial rotation (p = 0.011).

Similarly, tests were performed at Loyola University to investigate the ability of the TFAS, after destabilizing laminectomy–facetectomy, to restore dynamic stability with proper quality of motion to a surgically treated segment. Nine fresh-frozen human lumbar spines consisting of segments from L-1 to the sacrum were used for that study. The specimens were fixed at the caudal end and were free to move at the proximal end. The apparatus allowed continual cycling of the specimen between specified maximum moment end points in flexion and extension (8 Nm to –6 Nm), lateral bending (± 6 Nm), and axial rotation (± 5 Nm) applied to the L-1 vertebra. Flexion–extension motion was tested under a 400-N follower preload.

Specimens were tested intact and then after a complete L-3 laminectomy, with resection of the L-3 lower articular process performed using standard instruments and techniques. The L3–4 segment was then treated with a pedicle screw construct. Next, the TFAS was implanted at L3–4. The quantity and quality of motion at the implanted level were assessed in each testing condition (Fig. 5).

In that study, destabilization increased the flexion–extension ROM from 8.7 ± 2.0° in the intact status to 12.2 ± 3.2° (p < 0.01) after instrumentation. Fusion sig-
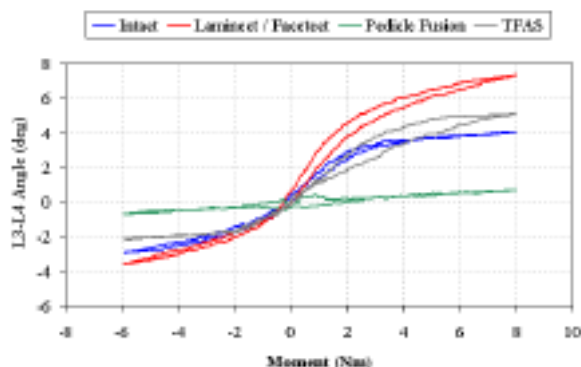
FIG. 5. Graph depicting an example of a load-displacement curve recorded during flexion–extension testing according to a 400-N preload protocol. deg = degrees; laminect/facetect = laminectomy/facetectomy.

FIG. 6. Bar graph showing the ROM of an L3–4 segment under a 400-N preload (asterisks indicate p < 0.05). The increments on the y axis denote ROM (degrees).

nificantly decreased ROM compared with intact status, resulting in 1.7 ± 0.5° of flexion–extension ROM (p < 0.01). The TFAS prosthesis restored motion to 7.9 ± 2.1°, which was not statistically different compared with intact status (p = 0.146) (Fig. 6). Destabilization also significantly increased the ROM for lateral bending, from 9.0 ± 2.5° to 10.2 ± 2.7° (p = 0.012). Fusion decreased lateral bending motion to 3.3 ± 1.4°, which was significant compared with intact spines (p < 0.01). The TFAS restored the lateral bending motion to 10.1 ± 3.0°, which was not significantly different from the intact state (p = 0.132). Destabilization increased axial rotation ROM from 3.8 ± 2.7° to 7.2 ± 3.9° (p = 0.001). Fusion reduced ROM 1.8 ± 0.6°; this was significant compared with the intact state (p < 0.0001). Finally, the TFAS restored axial rotation to 4.7 ± 1.6°, which was not significantly different from the intact spine (p = 0.156).

Discussion

Facet replacement may have an important role in the treatment of the degenerative lumbar spine. Fusion of one or two motion segments may not make a substantial difference in the total ROM of the entire lumbar spine; however, preserving flexibility of a motion segment may prevent adjacent-segment disease and may permit disc replacement, even when facet joints need to be removed. Stabilization of the lumbar spine without fusion has been infrequently practiced during the last decade.[14] As stated earlier, disc replacement could be seen as a partial joint replacement in the three-joint complex of the lumbar spine. In the presence of significant facet joint arthritis, disc replacement may not relieve pain. When radicular pain warrants decompression involving partial facetectomy, a disc replacement may destabilize the motion segment. Additionally, surgical approaches for spinal stenosis do not restore normal function. Decompression with removal of soft tissue and partial facetectomy might lead to instability, or at least alter normal mechanics. Iatrogenic instability can lead to further degeneration and pain. Nonetheless, any facet replacement device will require a significant amount of validation testing as well as controlled clinical studies before being brought to market.
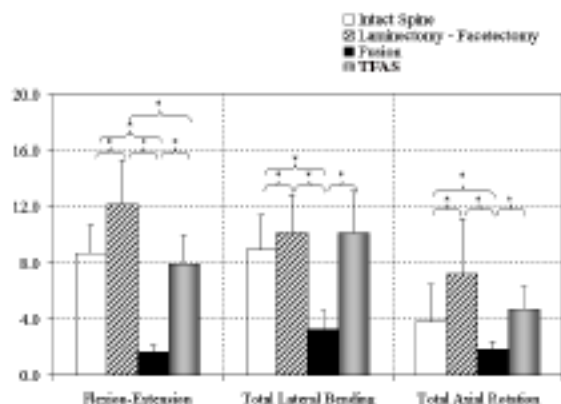
Isolated thinking about treatments for a degenerative diseased disc is giving way to more global considerations of FSU and adjacent-segment disease management. The development and potential application of facet arthroplasty and/or combined three-joint complex replacements may represent the new generation of spinal motion preservation technologies and is a reflection of this paradigm shift in philosophy. Although the potential surgical application of these technologies for the purposes of treating spinal disease is both exciting and thought-provoking, the challenges that exist are formidable, and on initial consideration the application of this technology in the treatment of spinal disease would seem questionable.

The well-known and basic tenets of arthroplasty treatments in orthopedics should be considered. In general, it is well known and accepted that the major factors that lead to success or failure of arthroplasty are as follows: 1) size of the joint surface (stress at the joint surface); 2) degree and extent of multiplanar motion and/or load transfer through the device or joint; 3) strength and size of the anchor points; and 4) long-term performance. With these factors in mind, by pure biomechanical and historical clinical application of joint arthroplasty technologies, facet joint replacement must then be viewed with skepticism; small joints that, by functional design, are required to accept multiplanar force application of substantial load with small anchoring points in essence would violate the basic tenets of successful joint replacement principles. However, in this paper we describe and review the foundations of biomechanical function of the lumbar facet joints and provide the framework to consider what works.

The facet joints, as White and Panjabi have eloquently described, are best viewed as part of a functional unit. These would include the facet joints themselves, the lamina and spinous processes, and of course the intervertebral disc. However, there is one other very important and underappreciated or rather obvious anatomical structure—the pedicle. The pedicles transmit tension and bending forces to the vertebral bodies. In the context of established, successful arthroplasty principles, the forces that the pedicles must accommodate are much more favorable. If we accept the concept of the posterior elements as two functional units in the three-joint complex, we must then

acknowledge the pedicle as the anatomical and physiological bridge for the force and as the structural connection between the posterior elements and the vertebral body. Indeed, in the leading companies in which work is proceeding on these technologies, this connection has been taken into consideration. Researchers at Archus Orthopedics, Inc., have recommended cementing their device by using an interpedicular fixation system. The technologies in development are based on the total removal of the facet joints and their replacement with artificial implants. In essence then, what must be considered is not just that the facet joints are being replaced, but that removal and replacement of the posterior anatomical FSUs as a whole is being performed. If the technologies presently being studied were evaluated and optimized for in vitro biomechanical performance, then their clinical success or failure would be highly dependent on their connection to the vertebral column (that is, the pedicle).

Prior to application of these systems, other factors that must be considered and studied include the level of the lumbar vertebra being treated, the type of arthroplasty device being used, and the lumbar spinal disorder being treated. Clearly questions remain and the challenges are formidable; nevertheless, the technologies being developed broaden our horizons and both inform and deepen our understanding of the treatment of spinal disorders.

Conclusions

At the present time in North America there is a great deal of enthusiasm about the introduction of total disc arthroplasty for the treatment of degenerative disc disease. To maximize the clinical benefit, understanding of the origins of back pain must also evolve as a necessary companion to the rapid advancements in motion preservation technologies. Our current focus continues to be on interventions and devices that relieve discogenic pain and reestablish the structure and normal function of the spine. We are now entering the era of partial and complete FSU replacement. The shift in usage of motion-sparing technology to replace a portion of arthrodesis procedures will most likely occur in the near future. Nevertheless, indications for facet replacements and posterior stabilization systems are still broad and unproven, and should be carefully considered. Furthermore, no prospective randomized controlled trial has been completed on these devices yet, which is an essential need for the practice of evidence-based medicine.

Disclaimer

The authors have no direct financial interest in any of the products or processes described in this paper.

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