In vitro measurement of load-sharing in spinal implants

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Abstract:

Efficient load-sharing in the spinal column relies on the proper working of the components of the Functional Spinal Unit (FSU). Due to various reasons such as trauma, ageing and diseases, these components or even the entire FSU can get degenerated or injured during a person's lifetime. Spinal column reconstruction surgeries were created with the aim to restore the functioning of the diseased or injured spine. Several spinal implants are available today for the surgeon to aid in this process. There are three major categories of these devices: anterior stabilization devices, posterior stabilization devices and motion preservation devices. This review highlights the *in vitro* research done on these devices, over the past five decades, to evaluate their ability to effectively share loads at the operated level of the spinal column. Some conclusions have been drawn based on this research. Dynamic anterior cervical plates are more successful at maintaining load-sharing after graft subsidence and anterior stabilization devices can be used to provide support to posterior stabilization devices during severe anterior column injuries. Motion preservation devices, specifically cervical disc prostheses and facet replacement systems, show great potential in maintaining physiological loads in the spinal column. Further clinical investigation of all these implants would help to identify the contributing factors for their success or failure post-surgery. It would also aid in determining the requirements of an ideal spine stabilization device which perfectly mimics the physiological load-sharing properties of the FSU and its components.

1. Introduction:

The various components of a spinal column enable a person to carry out any physical activity in his/her daily life such as standing, walking, lying, jumping, etc. They do so by providing a well-defined path for proper transfer of the loads (generated due to these activities) through the spinal column. Attempts to delineate this path go back at least six decades when Nachemson et al in the 1960's performed the first *in vivo* measurements of lumbar Intradiscal Pressure (IDP) using a needle pressure transducer with a polyethylene membrane tip. [15] IDP is developed in a healthy intervertebral disc (IVD) due to the presence of the Nucleus Pulposus (NP) which exerts hydrostatic pressure on the surrounding annulus. The Pressure Transducer was placed in the Nucleus Pulposus of a lumbar IVD to measure the IDP of healthy volunteers while they performed different physical activities. The results obtained from these studies were the foundation of many back-pain rehabilitation programs and for further investigations into the mechanism of load-transmission through the spinal column. [26] They also spurred the development of different techniques to estimate loads transferred through individual components of a Functional Spinal Unit (FSU) which include the two adjacent vertebrae, the intervertebral disc and all the ligaments connecting them.

Spinal loads can be estimated via *in vivo, in vitro* and computational methods. They range from pressure needle transducers in intervertebral discs [14] to 3-D computational models of the human spine [12, 16, 22]. *In vivo* measurements of the spinal loads such as the IDP measurements by Nachemson et al [15] and Wilke et al [26] have helped to establish the loading limits during *in vitro* testing of the spine. *In vitro* studies are fairly common in the field because they don't involve invasive surgeries on live humans. They help to quantify the working of various spinal implants before they are applied in the clinic and also provide validation of the several Finite Element models of the spine. [12, 16, 22] There are six main types of devices that measure either strain or pressure. These include Strain gauges (SG), Load cells (LC), Extensometers, Pressure sensitive films (Fujifilm), Digital pressure films, and Pressure needle transducers (PNT). Each of them has evolved over time. For example, the number of strain gauges to measure facet loads and their precise location on the vertebrae was optimized by Buttermann et al, in the 1990's. [6]

Development of customizable load cells based on the principle of strain gauges with variable height to measure intervertebral loads and to determine the adequate height of the interbody graft is another such example. [7, 17, 20] Pressure films advanced from single-use Fujifilm [13, 25] to re-usable digital film to improve their accuracy and to reduce the amount of films used per study. [3, 4, 9, 23] And, simple PNT's initially developed by Nachemson in 1960 [14] have grown into more sophisticated pressure and force sensors that can less-invasively and more accurately measure intradiscal pressure *in vivo* and *in vitro*. [10, 24] Researchers have also extensively tested the repeatability and accuracy of each of these techniques. [2, 13, 27]

This review discusses *in vitro* studies that have applied these six techniques to measure loads and to comprehend their path through the operated or instrumented level of the degenerated or injured spinal column. According to Wolff's law, the forces or loads exerted on a bone, especially after an injury, influence the strength of the remodeled bone. [28] Hence, it is essential that surgical interventions relying on bone fusion do not negatively affect the remodeling process. Load-shielding is a phenomenon that occurs when the applied load is transmitted through the spinal implant instead of the bone graft, potentially inhibiting fusion. To ensure proper remodeling, appropriate load-transfer through the bone graft is imperative. This is investigated *in vitro* via load-sharing studies discussed in the next section which draw conclusions on the importance of stabilization devices for improving arthrodesis and stability of the spinal column post-operatively. It is divided into three sub-sections according to the three main types of stabilization devices used which include anterior stabilization devices, posterior stabilization devices, and motion preservation devices, which include cervical disc prostheses and facet replacement systems.

2. Role of interbody grafts and stabilization devices in load-sharing at the operated level:

2.1. Anterior Stabilization Devices:

The Anterior Cervical Discectomy and Fusion (ACDF) procedure for treating cervical spine diseases and injuries involves the introduction of a bone graft in the intervertebral space after discectomy (removal of IVD) with the goal of fusion of the two cervical vertebrae above and below the disc. The adequate height of the graft introduced was an important parameter that was first determined in an *in vitro* study by Olsewski et al. [17] To determine this, load-sharing between the anteriorly placed graft and the posterior elements of cervical vertebrae was estimated. For this, a load cell graft, which consisted of a ‘subminiature load cell’ with metal load shims that would alter the height of the graft while maintaining the load transmission through the vertebral body to the LC, was used to measure anterior column load. Strain gages were applied to measure the loads through the posterior elements. When the height of the graft went beyond 3 mm, it was observed that the load transferred through the posterior ligaments decreased significantly. This value was in agreement with clinical recommendations. Thus, it was concluded that the adequate intervertebral distraction should be 3 mm to prevent graft collapse and pseudoarthrosis following the ACDF procedure.

Anterior Cervical Plates (ACP) were introduced to improve the rate of fusion after ACDF. However, it was unclear whether they would lead to load-shielding or load-sharing in the interbody bone graft introduced during the procedure. Therefore, Rapoff et al conducted a study to shed some light on this issue. [18] An extensometer was mounted on the lateral-anterior aspect of the cranial and caudal vertebral bodies of three-FSU bovine cadavers containing an interbody graft with or without a Cervical Spine Locking Plate (CSLP) system. CSLP is a constrained (or rigid) plate which does not allow rotation or translation of the screws with respect to the plate thus limiting the intervertebral motion. The interbody displacement was measured by the extensometer. This was converted to the graft and plate loads. The results showed that the absolute load through the graft increased with increasing applied axial load. Hence, the plate did not hinder loads through the graft which was required to ensure faster arthrodesis. In a follow-up study by Rapoff in 2003, the effect of two new anterior cervical plates (Premier and Zephir) on the load sharing between them and the ACDF graft was examined using a similar procedure. [19] Both were semi-constrained plates. Premier allowed both translation and rotation of screws while Zephir just allowed rotation. The applied load was measured using a load cell while intervertebral displacement was measured by an extensometer. No significant difference was found between the loads transmitted via the two plates but they were significantly higher than through the fully constrained CSLP system. Therefore, semi-constrained (or dynamic) plates were considered to be better at load-sharing and achieving arthrodesis than constrained plates.

Dynamic plates were, therefore, the next generation of anterior cervical plates that were developed to improve fusion rates by increasing load-sharing between the graft and the plate. However, whether this improvement was at the cost of stiffness was investigated by Brodke et al utilizing Digital pressure film and UHMWPE vertebral body models after a simulated corpectomy. [3] Four plating systems (2 dynamic and 2 static) were tested. The load through the graft was estimated by placing the film at the graft-vertebral body interface. A 10% graft subsidence was also simulated to investigate the changes in load-sharing among the plating systems. The results indicated that all the plating systems had similar load-sharing properties for a complete graft, but after subsidence, the dynamic plates were more effective in load-sharing than the static plates. These results did not agree with the afore-mentioned study where the graft load sharing for CSLP was considerably less. [19] However, it is not possible to directly compare the two studies as the approaches to determine graft loads were different. The stiffness of three of the plating systems (2 static and 1 dynamic) was significantly higher than that of the other dynamic plate. This indicated that the stiffness in dynamic systems depends on the plate design. This study was later replicated in human cervical spine segments by Brodke et al. [5] Three plating systems were compared (static, rotationally dynamic and translationally dynamic). The load-sharing with the full-length graft was similar for all the three systems and was also similar to that obtained by Rapoff et al. [18, 19] Moreover, the results of the previous study for 10% graft subsidence were confirmed, i.e., both the dynamic plates performed significantly higher load-sharing than the rigid system. This implies that during graft subsidence the static system causes the graft to lose its influence on the construct stiffness which is prevented by the dynamic system.

Brodke et al also performed a similar study in 2003 where they compared the load-sharing and stiffness properties of six different anterior thoracolumbar systems (3 rod-style and 3 plate-style systems) using UHMWPE models and digital pressure film to measure anterior column load, with and without an intervertebral graft after a simulated corpectomy. [4] Rod-style systems are more flexible than the plate-style systems and are expected to lead to higher load-transfer through the grafts. However, the results showed that the amount of load sharing, varying from 63% to 89%, did not depend on the style (rod or plate) of the stabilization system and was inversely proportional to the stiffness of the system. The presence of the graft was found to be essential for overall stiffness of the construct.

In another study in 2003 by Yang and Wang, the effects of two types of differently constrained plate systems on load-transfer through the graft (PMMA) were compared by using a blade-type extensometer on the anterior portion of the vertebral body to measure strain through the spine. [29] An equation was used to convert this strain to load through the graft and through the plate-facet joint system. The results showed that the amount of load-sharing was similar for both types of plates and both of them provided adequate stability to the system. The minor difference in the two plates' stabilization of the construct was construed to be due to differences in the plates' geometries and not their material properties.

The effect of type of anterior cervical plate (static versus dynamic) used, graft height and presence of posterior elements on the load sharing between graft and plate in human cervical spines was examined by Reidy et al. [20] A height adjustable subminiature load cell graft measured the graft load and two strain gauges measured the plate load. The load through the posterior elements was the difference between the applied load and the sum of graft and plate loads. Static plate was simulated by modifying the dynamic plate. Results showed significantly higher load passing through the graft with dynamic plating especially for the undersized graft. This key study agreed with previous studies performed on animal and UHMWPE models. It suggested that the plating systems designed in the future for the ACDF procedure should depend on whether the spine was degenerated or injured because in the latter case, the posterior elements may be compromised, which were found to play an important role in load-transfer especially under graft subsidence.

The newest generation of anterior cervical plates are the Bioresorbable plates which can be assimilated by cellular activity and disappear once their work of providing immediate post-operative stability and graft-containment is done. A study by Freeman et al, investigated the effects of the bioresorbable plates versus the 'gold standard' titanium plates on the load-sharing between the plate and the graft after a simulated ACDF. [11] It was observed that the bioresorbable plates allowed for more load-sharing with the graft (wooden) than the titanium plates under both physiologic static and cyclic loading conditions. They also remained intact and provided stability to the system during the entire testing procedure. In another study by Cheng et al, load-sharing characteristics of biodegradable and titanium plates were compared for a cervical discectomy model containing an interbody spacer. [7] The spacer was fitted with a subminiature LC with a high capacity (1112 N) with endplate components (to vary its height) similar to an interbody implant to directly measure axial loads through the anterior column. This was the first study to use a load cell that was customized to resemble an interbody implant to directly measure anterior column loads. Three conditions were compared: spacer alone, spacer with biodegradable polymer plate or with rigid titanium plate. No significant difference in load-sharing was observed among the three conditions, but both the plates significantly improved stability of the segments as compared to just the spacer. Bioresorbable plates have been clinically studied as well but the sample size of these studies was small. They were found to work as well as metal plates in one study done over a year and led to fusion and increased stability over 5-7 years of follow up in another study. [1, 21]

Therefore, it is clear from these studies that the presence of an anterior cervical plate leads to load-sharing and not load-shielding. The performance of dynamic plates is similar to that of the rigid plates for a full graft but they tend to stabilize the graft better during its subsidence. Bioresorbable plates have not shown any significant advantage in load-sharing over the dynamic and rigid plate systems. Thus, the efficacy of an anterior stabilization device in achieving arthrodesis may not solely depend on its flexibility.

2.2. Posterior Stabilization Devices:

Posterior stabilization devices that provide immediate post-operative stability and improve chances of arthrodesis in the spinal column have also evolved in parallel with anterior stabilization devices. Cripton et al investigated the load-sharing properties of lumbar spine segments after being stabilized with a rigid posterior implant. [10] Uniaxial strain gauges were used to create six-axis load cells to measure loads and forces through these implants and pressure transducers measured the IDP. The authors concluded that these implants were not suitable for highly severe anterior column injuries in the absence of anterior stabilization systems because these devices would lead to higher load-sharing through the anterior column which being weak early in recovery and without support from anterior implants might not be able to handle those loads.

Posterior dynamic stabilization (PDS) devices were introduced to ensure higher chances of arthrodesis and better anterior column loading. Yu et al compared the ISOBAR PDS system to rigid titanium rods in human lumbar spine segments. [30] A TLIF (Trans-foraminal Lumbar Interbody Fusion) procedure was performed on the specimens and a special TLIF cage with an integrated 'uniaxial' load cell was introduced. The height of the load cell could be varied to fit each FSU. Biomechanical testing indicated that the Isobar system led to significantly higher anterior column loading than the rigid rods under axial compression while the stabilization of Isobar system was similar to that of the rigid rod. The authors concluded that the uniaxial load cells were limited in utility since they could not provide a measurement of the moments transferred through the interbody graft. The authors concluded that the Isobar system has the potential to improve rates of arthrodesis and further clinical studies were suggested to confirm this.

In another study by Sengupta et al, the load-sharing between the anterior column of a UHMWPE vertebral body model with an interbody spacer and three types of posterior stabilization devices (Rigid rods, PEEK rods and PDS systems) was analyzed. [23] The upper end of the spacer was flat while the lower end was not due to the presence of 'bone graft windows' and therefore, the digital pressure film was placed between the 'superior' body and the spacer to ensure the absence of any pressure artifacts. The data obtained from the pressure film was used to calculate the anterior column load and the pressure maps created were used to visualize the load distribution through the spacer itself. This gave the researchers a better idea of how the load being transferred from the body to the spacer varied due to the different posterior stabilization systems. The posterior dynamic stabilization system behaved most similarly to a physiological system as compared to rigid and semi-rigid PEEK systems because the amount of load transferred through the anterior column was significantly greater with PDS compared to the other two systems. Moreover, the contact pressures were uniform throughout the disc with PDS and had smaller peak pressures on any point in the disc.

One of the latest studies to examine the load-sharing properties of a PDS system utilized a novel approach for calculating the anterior column load through an interbody spacer. [9] The study was performed by Cook et al on cadaveric human lumbar spine specimens instead of UHMWPE models. The spacer was a PEEK ALIF cage which had a graft window on the top and an anterior window for a digital pressure film, so that it was in direct contact with the graft and exposed to a completely flat surface to avoid errors in pressure measurement during biomechanical testing. This also allowed tri-axial load measurement in cadaver specimens. The difference in load-sharing properties of the TRANSITION PDS system and Titanium rods was analyzed and it was concluded that there were no significant differences between the two systems in terms of load-sharing properties. However, the use of titanium rods led to significantly lower graft loading as compared to graft only specimen in flexion, while there was no significant difference in graft loading between the graft only and PDS system specimens. Moreover, the stabilization achieved by both the systems was also similar which the authors attributed to the presence of the interbody graft and not the devices.

The studies discussed here showed that PDS devices allow load-sharing but they may or may not be more efficacious than rigid posterior systems. The rigid systems may also lead to excess load-transfer through the anterior column which can’t be handled without anterior plates. Nevertheless, clinical validation through long-term investigations can improve our understanding of these systems.

2.3. Cervical Disc Prostheses and Facet Replacement Systems:

Cervical disc prostheses are used for IVD replacement and a pilot study by Stieber et al investigated the effects of such a prosthesis on the facet joint loading profile. [25] This prosthesis had a unique design with saddle-shaped articulation to maintain physiological facet joint loading. The study used a thin film ink resistor overlaid with Fujifilm to measure pressure through the facet joints in the intact ovine cervical disc and the prosthetic disc. To insert the sensor, an arthrotomy of the superior facet was performed, but the capsular ligaments were preserved. No statistical differences in peak pressure, mean pressure, total force through the facets were observed between the native and prosthetic disc conditions. However, a significant decrease in facet contact area was observed for the prosthetic disc as compared to the native disc which was attributed to the size of the prosthetic. The implications of these results were not clear but another study was performed to investigate the complete biomechanical profile of the same prosthetic disc and compare it with anterior plating by Colle et al. [8] The facet loads were measured using SG's. The facet loads were not significantly different after prosthetic or plate insertion compared to intact condition. However, an increase in overall mean facet load after disc insertion was seen in extension which was attributed to improper disc insertion.

Facet replacement systems are another set of motion-preservation devices that have recently been developed. A combined *ex vivo* and FEM study was conducted by Sjovold et al to investigate the load-sharing characteristics of the new and dynamic Total Facet Arthroplasty System (TFAS) implant compared to the conventional rigid UCR implant. [24] The TFAS system models an intact facet and has been designed to simulate the loading profile of a facet joint. To delineate this profile for TFAS, PNT's were used to measure IDP while uniaxial SG's measured the implant loads placed on human lumbosacral spine specimens which had undergone laminectomy and bilateral facetectomy. The TFAS system was found to produce pressure values similar to an intact lumbar spine, thus, maintaining the normal load sharing characteristics.

Motion-preservation devices, such as the ones discussed above, have been designed to mimic the natural functions of the components of the FSU. They were found to behave similarly to the physiological IVD and the facet joints in these studies. Such favorable results warrant further investigation of the effects of different designs and different placements of these devices on the load-sharing in the spinal column.

3. Summary and Conclusions:

This review discussed *in vitro* studies performed on human and animal cadaveric specimens and UHMWPE models to comprehend the changes in the load-sharing properties of the spinal column after introduction of an interbody graft and/or a stabilization device following degeneration or injury in the spine. Three types of stabilization devices were considered: anterior stabilization devices, posterior stabilization devices and motion preservation devices. These devices have evolved over the past few decades and have provided relief to patients for whom rehabilitation programs and physiotherapy are not effective.

Anterior stabilization devices have been extensively utilized to reconstruct the cervical and thoracolumbar regions of the spine. They range from plate systems which may be fully constrained or semi-constrained and made up of titanium, biodegradable polymers, etc. to the more flexible rod style systems used in the thoracolumbar regions. They improve load-sharing in the graft post-operatively independent of their flexibility. However, dynamic cervical plates were shown to maintain load-sharing in a partially subsided graft unlike rigid cervical plates. Future plate designs should consider whether the spine was injured or degenerated prior to surgery to improve load-distribution and rate of arthrodesis.

Posterior stabilization devices, similarly, range from rigid to semi-rigid to dynamic (PDS) depending on the material used. They have mostly been utilized to reconstruct the lumbar spine. Flexibility is not the final determinant of efficient load-sharing in this case as well. However, anterior stabilization systems in conjunction with posterior stabilization systems may be more effective in improving arthrodesis rates when severe anterior column injuries occur. Motion preservation devices are the least investigated of the three types. But they show great potential in maintaining the physiological loads in the spinal column.

Despite several *in vitro* studies that have been conducted over the past few decades, the factors contributing to the success of a spinal implant post-surgery are still unclear. Currently surgeons rely on factors such as the ease of use and familiarity with the device for selecting a particular implant. [4, 30] Therefore, further long-term clinical investigation of these devices is essential to understand the reasons for success of one device over the other and for designing the ideal implant for reconstruction of the diseased or injured spinal column.

References:

1. Aryan, H. E., Lu, D. C., Acosta, F. L., Hartl, R., Mccormick, P. W., & Ames, C. P. (2007). Bioabsorbable Anterior Cervical Plating. *Spine*, *32*(10), 1084-1088. doi: 10.1097/01.brs.0000261489.66229.c1
2. Brimacombe, J. M., Wilson, D. R., Hodgson, A. J., Ho, K. C., & Anglin, C. (2009). Effect of Calibration Method on Tekscan Sensor Accuracy. *Journal of Biomechanical Engineering J. Biomech. Eng.*, *131*(3), 034503. doi:10.1115/1.3005165
3. Brodke, D. S., Gollogly, S., Mohr, R. A., Nguyen, B., Dailey, A. T., & Bachus, K. N. (2001). Dynamic Cervical Plates. *Spine*, *26*(12), 1324-1329. doi:10.1097/00007632-200106150-00010
4. Brodke, D. S., Gollogly, S., Bachus, K. N., Mohr, R. A., & Nguyen, B. N. (2003). Anterior Thoracolumbar Instrumentation: Stiffness and Load Sharing Characteristics of Plate and Rod Systems. *Spine*, *28*(16), 1794-1801. doi: 10.1097/01.brs.0000083201.55495.0e
5. Brodke, D. S. (2006). Anterior Cervical Fixation: Analysis of Load-Sharing and Stability with Use of Static and Dynamic Plates. *The Journal of Bone and Joint Surgery (American) J Bone Joint Surg Am*, *88*(7), 1566. doi:10.2106/jbjs.e.00305
6. Buttermann, G. R., Kahmann, R. D., Lewis, J. L., & Bradford, D. S. (1991). An Experimental Method for Measuring Force on the Spinal Facet Joint: Description and Application of the Method. *Journal of Biomechanical Engineering J. Biomech. Eng.*, *113*(4), 375. doi:10.1115/1.2895415
7. Cheng, B. C., Burns, P., Pirris, S., & Welch, W. C. (2009). Load Sharing and Stabilization Effects of Anterior Cervical Devices. *Journal of Spinal Disorders & Techniques*, *22*(8), 571-577. doi:10.1097/bsd.0b013e31818eee78
8. Colle, K. O., Butler, J. B., Reyes, P. M., Newcomb, A. G., Theodore, N., & Crawford, N. R. (2013). Biomechanical evaluation of a metal-on-metal cervical intervertebral disc prosthesis. *The Spine Journal*, *13*(11), 1640-1649. doi:10.1016/j.spinee.2013.06.026
9. Cook, D., Yeager, M., Thampi, S., Whiting, D., & Cheng, B. (2015). Stability and Load Sharing Characteristics of a Posterior Dynamic Stabilization Device. *Int J Spine Surg International Journal of Spine Surgery*, *9*. doi:10.14444/2009
10. Cripton, P. A., Jain, G. M., Wittenberg, R. H., & Nolte, L. (2000). Load-Sharing

Characteristics of Stabilized Lumbar Spine Segments. *Spine, 25*(2), 170. doi:10.1097/00007632-200001150-00006

11. Freeman, A. L., Derincek, A., Beaubien, B. P., Buttermann, G. R., Lew, W. D., & Wood, K. B. (2006). *In Vitro* Comparison of Bioresorbable and Titanium Anterior Cervical Plates in the Immediate Postoperative Condition. Journal of Spinal Disorders & Techniques, 19(8), 577-583. doi:10.1097/01.bsd.0000211228.81930.c9

12. Goel, V. K., & Clausen, J. D. (1998). Prediction of Load Sharing Among Spinal Components of a C5-C6 Motion Segment Using the Finite Element Approach. Spine, 23(6), 684-691. doi:10.1097/00007632-199803150-00008

13. Hedman, T. P. (1992). A new transducer for facet force measurement in the lumbar spine: Benchmark and *in vitro* test results. Journal of Biomechanics, 25(1), 69-80. doi:10.1016/0021-9290(92)90246-w

14. Nachemson, A. (1960). Lumbar Intradiscal Pressure: Experimental Studies on Post-Mortem Material. Acta Orthopaedica Scandinavica, 31(Sup43), 1-104. doi:10.3109/ort.1960.31.suppl-43.01

15. Nachemson, A., & Morris, J. (1964). *In Vivo* Measurements of Intradiscal Pressure. Journal of Bone and Joint Surgery, 46-A(5), 1077-1092.

16. Naserkhaki, S., Jaremko, J. L., Adeeb, S., & El-Rich, M. (2016). On the load-sharing along the ligamentous lumbosacral spine in flexed and extended postures: Finite element study. Journal of Biomechanics, 49(6), 974-982. doi:10.1016/j.jbiomech.2015.09.050

17. Olsewski, J. M., Garvey, T. A., & Schendel, M. J. (1994). Biomechanical Analysis of Facet and Graft Loading in a Smith-Robinson Type Cervical Spine Model. Spine, 19(Supplement), 2540-2544. doi:10.1097/00007632-199411001-00008

18. Rapoff, A. J., O??brien, T. J., Ghanayem, A. J., Heisey, D. M., & Zdeblick, T. A. (1999). Anterior Cervical Graft and Plate Load Sharing. Journal of SPINAL DISORDERS, 12(1). doi:10.1097/00002517-199902000-00007

19. Rapoff, A. J., Conrad, B. P., Johnson, W. M., Cordista, A., & Rechtine, G. R. (2003). Load Sharing in Premier and Zephir Anterior Cervical Plates. Spine, 28(24), 2648-2650. doi:10.1097/01.brs.0000099387.37393.3f

20. Reidy, D., Finkelstein, J., Nagpurkar, A., Mousavi, P., & Whyne, C. (2004). Cervical Spine Loading Characteristics in a Cadaveric C5 Corpectomy Model Using a Static and Dynamic Plate. Journal of Spinal Disorders, 17(2), 117-122. doi:10.1097/00024720-200404000-00008
21. Rodrigo, V., Maza, A., Calatayud, J., Bances, L., Diaz, F., Gimeno, M., & Carro, B. (2015). Long-term follow-up of anterior cervical discectomy and fusion with bioabsorbable plates and screws. Clinical Neurology and Neurosurgery, 136, 116-121. doi:10.1016/j.clineuro.2015.04.002
22. Rohlmann, A., Burra, N. K., Zander, T., & Bergmann, G. (2007). Comparison of the effects of bilateral posterior dynamic and rigid fixation devices on the loads in the lumbar spine: A finite element analysis. *European Spine Journal Eur Spine J,16*(8), 1223-1231. doi:10.1007/s00586-006-0292-8
23. Sengupta, D. K., Bucklen, B., Mcafee, P. C., Nichols, J., Angara, R., & Khalil, S. (2013). The Comprehensive Biomechanics and Load-Sharing of Semirigid PEEK and Semirigid Posterior Dynamic Stabilization Systems. *Advances in Orthopedics, 2013,* 1-9. doi:10.1155/2013/745610
24. Sjovold, S. G., Zhu, Q., Bowden, A., Larson, C. R., Bakker, P. M., Villarraga, M. L., Cripton, P. A. (2012). Biomechanical evaluation of the Total Facet Arthroplasty System® (TFAS®): Loading as compared to a rigid posterior instrumentation system. European Spine Journal Eur Spine J, 21(8), 1660-1673. doi:10.1007/s00586-012-2253-8
25. Stieber, J. R., Quirno, M., Kang, M., Valdevit, A., & Errico, T. J. (2011). The Facet Joint Loading Profile of a Cervical Intervertebral Disc Replacement Incorporating a Novel Saddle-shaped Articulation. Journal of Spinal Disorders & Techniques, 24(7), 432-436. doi:10.1097/bsd.0b013e3182027297
26. Wilke, H., Neef, P., Caimi, M., Hoogland, T., & Claes, L. E. (1999). New *In Vivo* Measurements of Pressures in the Intervertebral Disc in Daily Life. Spine, 24(8), 755-762. doi:10.1097/00007632-199904150-00005
27. Wilson, D. C., Niosi, C. A., Zhu, Q. A., Oxland, T. R., & Wilson, D. R. (2006). Accuracy and repeatability of a new method for measuring facet loads in the lumbar spine. Journal of Biomechanics, 39(2), 348-353. doi:10.1016/j.jbiomech.2004.12.011
28. Wolff, J. (1986). The law of bone remodelling. Berlin: Springer-Verlag.

29. Yang, S., & Wang, L. (2003). Biomechanical comparision of the stable efficacy of two anterior plating systems. Clinical Biomechanics, 18(6). doi:10.1016/s0268-0033(03)00086-x

30. Yu, A. K., Siegfried, C. M., Chew, B., Hobbs, J., Sabersky, A., Jho, D. J., Cheng, B. C. (2012). Biomechanics of Posterior Dynamic Fusion Systems in the Lumbar Spine. Journal of Spinal Disorders and Techniques, 1. doi:10.1097/bsd.0b013e31827588b1