NEW PROPOSAL FOR THE TREATMENT OF CORONAL SPLIT FRACTURES IN LUMBAR VERTEBRAE: THE FATIGUE CURVE

NOVA PROPOSTA DE TRATAMENTO DE FRATURAS DO TIPO SPLIT CORONAL EM VÉRTEBRAS LOMBARES: CURVA DE FADIGA

NUEVA PROPUESTA DE TRATAMIENTO DE FRACTURAS DEL TIPO SPLIT CORONAL EN VÉRTEBRAS LUMBARES: CURVA DE FATIGA

André Rafael Hubner,[1,2] Carlos Tobias Scortegagna,[1] Charles Leonardo Israel,[3,4,5] Everton Luis do Amarante Ivo,[3] Fabiano Favretto,[3] Marcelo Ribeiro,[6] Leandro de Freitas Spinelli[3,4,5,7,8]

1. Hospital São Vicente de Paulo, Instituto de Ortopedia e Traumatologia, Spine Surgery Service, Passo Fundo, RS, Brazil.
2. Hospital São Vicente de Paulo, Instituto de Ortopedia e Traumatologia, Medical Residency Program (Staff) in Orthopedics and Traumatology, Spine Fellowship Program, Passo Fundo, RS, Brazil.
3. Universidade de Passo Fundo, Department of Mechanical Engineering, Passo Fundo, RS, Brazil.
4. Universidade de Passo Fundo, Graduate Program in Manufacturing Projects and Processes, Passo Fundo, RS, Brazil.
5. Universidade de Passo Fundo, Bioengineering, Biomechanics and Biomaterials Laboratory, Passo Fundo, RS, Brazil.
6. Clínica Kozma, Passo Fundo, RS, Brazil.
7. Universidade Federal de Ciências da Saúde de Porto Alegre, Faculdade de Medicina, RS, Brazil.
8. Santa Casa de Misericórdia de Porto Alegre, Orthopedics and Traumatology Service, RS, Brazil.

ABSTRACT

Objective: To evaluate a new treatment for split fractures through fatigue tests on a swine model. Methods: Thirty lumbar spine samples (L2-L3-L4) from swine models were divided into three test groups. The first was the control group (intact vertebrae). In the second group, a bone defect was created, similar to a coronal split fracture of the vertebral body. For this, a bone defect (osteotomy) was performed in the coronal axis of the middle third of the middle lumbar vertebral body (L3), keeping the disc-ligament structures intact. In the third group, the same procedure was performed to cause bone failure, but was associated with the use of synthesis material, with pedicular fixation using 3.5 mm cannulated screws with partial thread, in order to apply compression at the fracture site, giving resistance and support to the vertebra. The groups were submitted to biomechanical fatigue tests. The number of cycles required to failure in the specimen was analyzed. Results: The use of the synthesis material increased the resistance of the fractured vertebrae to levels equal to those of the intact vertebra for low cycles with loads of 40% of the failure load, possibly losing up to 20% of their resistance for higher cycles. Conclusions: In the vertebrae in which synthetic material was used, greater resistance to a greater number of cycles for a longer period of time was observed when compared with the fractured vertebrae, suggesting that this is an interesting method for the fixation of split-type spinal fractures. ***Level of evidence III; Experimental Study.***

Keywords: Fracture; Models, Animal; Spine; Fatigue.

RESUMO

Objetivo: Avaliar um novo tratamento de fraturas do tipo separação (split) através de ensaios de fadiga em modelo suíno. Métodos: Trinta amostras de coluna lombar (L2-L3-L4) de modelos suínos foram divididas em três grupos para testes. O primeiro constituiu o grupo controle (vértebras intactas). No segundo grupo, foi criado um defeito ósseo semelhante a uma fratura split coronal do corpo vertebral. Para tanto, criou-se um defeito ósseo (osteotomia) no eixo coronal do terço médio do corpo vertebral intermediário lombar (L3), mantendo as estruturas disco-ligamentares íntegras. No terceiro grupo, foi realizado o mesmo procedimento para causar a falha óssea, sendo associado o uso de material de síntese, com a fixação pedicular com parafuso canulado de 3,5 mm com rosca parcial, com objetivo de realizar compressão no foco da fratura e dar resistência e sustentação à vertebra. Os grupos foram submetidos a testes biomecânicos de fadiga. Foi analisado o número de ciclos necessários para que ocorresse a falha no corpo de prova. Resultados: O material de síntese aumenta a resistência da vértebra fraturada em níveis iguais aos da vértebra intacta para baixos ciclos e com cargas de 40% da tensão de ruptura, podendo perder até 20% de sua resistência para ciclos mais altos. Conclusões: Nas vértebras em que foi utilizado material de síntese observou-se maior resistência ao maior número de ciclos por um período mais prolongado em comparação com as vértebras apenas fraturadas, sugerindo que este é um método interessante para a fixação de fraturas do tipo split na coluna vertebral. ***Nível de evidência III; Estudo experimental.***

Descritores: *Fratura; Modelos Animais; Coluna Vertebral; Fadiga.*

RESUMEN

Objetivo: Evaluar un nuevo tratamiento de fracturas lumbares del tipo separación (split) a través de ensayos de fatiga en modelo porcino. Métodos: Treinta muestras de columna lumbar (L2-L3-L4) de modelos porcinos fueron divididas en tres grupos para tests. El primero

Study conducted at the Bioengineering, Biomechanics and Biomaterials Laboratory of the Universidade de Passo Fundo and the Spine Surgery Service of the Hospital São Vicente de Paulo, Passo Fundo, RS, Brazil.
Correspondence: André Rafael Hubner. Rua Uruguai, 2050, Passo Fundo, RS. 99010-112. arhubner@terra.com.br

http://dx.doi.org/10.1590/S1808-185120212002235745

Received on 03/29/2020 accepted on 10/06/2020
Reviewed by: Cintia K. Bitta

constituyó el grupo control (vértebras intactas). En el segundo grupo, fue creado un defecto óseo semejante a una fractura split coronal del cuerpo vertebral. Para tanto, se creó un defecto óseo (osteotomía) en el eje coronal del tercio medio del cuerpo vertebral intermedio lumbar (L3), manteniendo las estructuras disco-ligamentarias íntegras. En el tercer grupo, fue realizado el mismo procedimiento para causar la falla ósea, siendo asociado el uso de material de síntesis, con fijación pedicular con tornillo canulado de 3,5 mm con rosca parcial, con el objetivo de realizar compresión en el foco de la fractura y dar resistencia y sustentación a la vértebra. Los grupos fueron sometidos a tests biomecánicos de fatiga. Fue analizado el número de ciclos necesarios para que ocurriese la falla en el cuerpo de prueba. Resultados: El material de síntesis aumenta la resistencia de la vértebra *fracturada en niveles iguales a los de la vértebra intacta para bajos ciclos y con cargas de 40% de la tensión de ruptura, pudiendo perder hasta 20% de su resistencia para ciclos más altos. Conclusiones: En las vértebras en que fue utilizado material de síntesis se observó mayor resistencia al mayor número de ciclos por un período más prolongado en comparación con las vértebras solamente fracturadas, sugiriendo que este es un método interesante para la fijación de fracturas de tipo split en columna vertebral.* ***Nivel de evidencia III; Estudio experimental.***

Descriptores: *Fractura; Modelos Animales; Columna Vertebral; Fatiga.*

INTRODUCTION

Coronal split fractures are well-recognized and well-differentiated from compression/wedge fractures of the vertebral body due to the peculiarity of their fracture line. There are few reports about this injury or about its treatment in the literature. The mechanism of this fracture is compression by axial load. The fracture is characterized by upper disc injury, crushing of the terminal plate and coronal cleavage of the vertebral body. The impaction injury of the vertebral body, resulting in a split fracture in the frontal plane, is classified by the AO system as a type A2 fracture. Roy-Camille and Lelièvre[1] proposed that this type of fracture be treated by posterior approach fixation with pedicle screws. Normally, the fracture consolidates regardless of the type of treatment and pseudoarthrosis of the vertebral body is rare after conservative treatment.[2] Gaines and Humphreys[3] state that in this type of fracture bone consolidation will not occur without surgical treatment.

The thoracolumbar region is the most frequent site of spine fractures, especially at the T12-L1 level.[4,5] According to Magerl et al.,[6] burst type fractures were found in 66.1% of the cases evaluated. In A2 fractures, the middle and posterior spines are preserved and they are classified as stable fractures. Patients with compression fractures, such as the coronal split fracture, mainly receive conservative treatment because they rarely present neurological deficits.[7] As conservative treatment, a thoracolumbosacral orthosis (TLSO) is applied for 8 to 12 weeks.[8,9] The treatment prognosis usually appears to be good, but a small number of patients may experience persistent pain after the fracture is completely healed.[10,11]

However, surgical treatment may be necessary for coronal split fractures, as nonunion or pseudoarthrosis can occur due to invagination of the disc material at the fracture site.[6,12] Short segment instrumentation or long segment fusion can be chosen as the treatment option depending on the situation. Currently, satisfactory results are being reported by performing short segment instrumentation with fusion.[13]

In this study, we are proposing an assessment of the behavior of coronal split fractures using fatigue tests. Different from the conventional synthesis applied, the posterior approach using pedicle screws combined with rods, the proposal of the present study was to use cannulated titanium spongy-thread screws 3.5 mm in diameter and 40 mm in length. The objective was to analyze the number of cycles that the fractured vertebral bodies could withstand against the cyclic axial loads of the fatigue machine compared to a set of intact vertebrae submitted to the same loads under the same biomechanical conditions.

METHODS

This is an experimental study that performed fatigue tests using sections of lumbar swine vertebrae. A total of 30 spinal segments from L2-L4 were used, maintaining the integrity of the vertebral bodies, ligaments and intervertebral discs of the material obtained. The choice of the lower lumbar spine provided larger vertebral bodies and was used due to the insertion of synthesis materials.

Animals of the Landrace breed with a mean age of 4.5 months and mean weight of approximately 120 kg were used, based on the studies by Busscher et al.[14] The samples were obtained from a fridge and no live animals were handled.

The models were prepared in order to be submitted to cyclic axial compression. In all the groups, excess muscle was removed from the vertebral segment, preserving the intervertebral discs, ligaments and nerve tissue. In the groups containing fractures, after cleaning, the bone injury was performed (type A2 fracture – coronal split) in 20 samples by coronal vertebral division with the aid of a Stryker® surgical pneumatic oscillating saw and surgical chisel. (Figure 1)

In 10 specimens the synthesis material was used for compression at the location of the fracture. Aided by a Stryker® pneumatic drill and using a Kirschner wire as a guide, the point of entry was made for placement of the cannulated screws with spongy hexagonal thread and diameter of 3.5 mm, thread pitch of 1.25 mm and length of 40 mm, and compression of the fracture line was performed. (Figure 2)

After the technical procedures on the vertebrae being studied were completed, the specimens were kept at a temperature of -20ºC until the tests were performed, when they were thawed for about 12h in a 0.9% saline solution and sealed in a plastic bag to rehydrate them, according to Adams.[15] The spine models were analyzed by computed tomography (Toshiba® Aquilion 128-slice) to check the fracture pattern and, in those that had synthesis material, to also confirm whether it had reached the fractured part of vertebra L3 and was not in the spinal canal or outside the pedicle. (Figure 3)

Considering the stability necessary, with no buckling of the model at the beginning of the application of the load, a specific device was used for the study, introduced into the vertebral canal in order

Figure 1. Fracture by coronal division performed.

to restrict lateral movement, flexion and extension of the specimen, allowing only axial forces to be applied. Because there is no specific standard for compression tests on organic materials, the ASTM E9-89a and ASTM F1717 standards used in static and fatigue tests on spinal implants, which define the compression test for metallic materials,[16,17] were considered. Shimadzu equipment was used to perform the fatigue tests. (Figure 4)

The maximum failure load found for these specimens in the static regime occurs between 7kN and 10kN (Hubner et al).[25] Loads at 40%, 60%, 70% and 80% of the maximum failure load were considered, following the test model executed by Parkinson et al.,[18] Failure of the specimen was defined as the moment when the force versus displacement curve shows a sudden drop.[19] The S-N curve was established from the data obtained.

Statistical analysis was initially conducted with the Brown Forsythe and Bartlett test to verify the homogeneity of the variances of the results obtained in the different groups of vertebrae. Normality analysis of the results was performed using the Shapiro-Wilk test. When normality was not observed, the results were transformed using the Box-Cox method. The comparison of the means of the number of cycles supported by the different groups of vertebrae under the different applied loads was performed through analysis of variance (single factor ANOVA) followed by the Tukey test. All statistical analysis was conducted using Statistica® 7.0 software (Statsoft Inc., Tulsa, OK, USA) with a confidence interval of 95%. The p-values obtained in the different Brown Forsythe, Bartlett and Shapiro-Wilk tests, as well as the lambda values used in the Box-Cox transformation are attached.

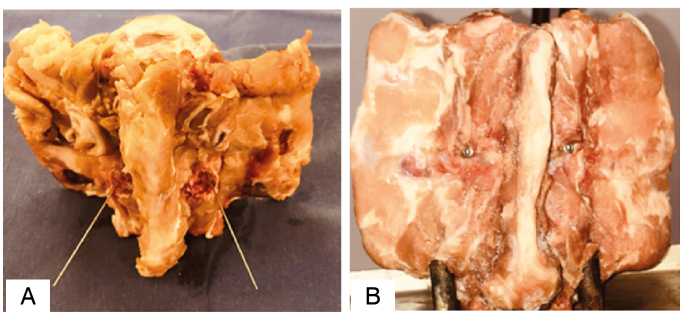


Figure 2. (A) Segment of swine lumbar vertebrae L2-L3-L4 model showing the Kirschner wires at the entry point used as a guide, (B) Post-fixation of the fracture line with cannulated screws.

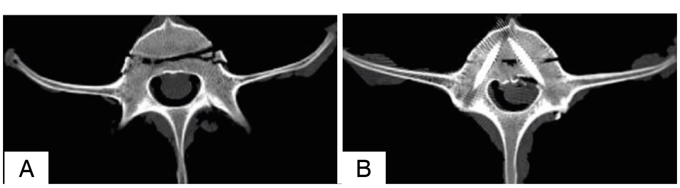


Figure 3. (A) Computed tomography of lumbar segment L3 vertebra after coronal split fracture (B) Computed tomography of lumbar vertebra L3 after osteosynthesis with cannulated screw, pedicular fixation.

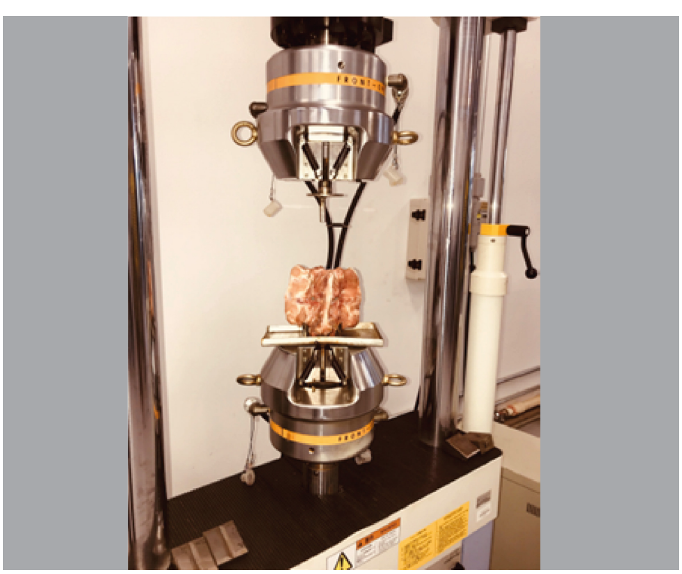


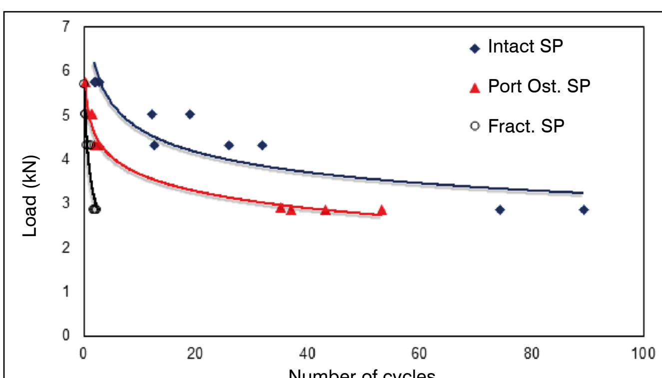
Figure 4. Equipment used for the fatigue test.

RESULTS

Figure 5 shows that, as the load increases in the tests, the number of cycles to failure decreases, i.e., a high compressive load has a lower number of cycles until the failure of the specimen, while a low load determines a higher number of cycles until failure. Figure 5 presents the results obtained for the different groups in an S-N-type graph. In the graph, it can be seen that the fractured specimens operated on using the proposed technique presented similar behaviors, but supported a slightly lower load. The fractured untreated specimens basically did not support load cycles.

Using failure cycles of 40% of the maximum value, i.e., 2872N, we obtained a mean of 81,810 cycles in the intact vertebrae, 42,145 cycles to failure in the group with synthesis and a mean of 1980 cycles until failure in the group without synthesis. At a load of 60%, of the established maximum, or 4308N, we obtained a mean of 23,505 in the control group, 2410 in the group with synthesis compared to 860 cycles to failure in the group without synthesis. In the test at 70% load, 5026N, the results were 15,592 cycles in the vertebrae without fracture, 1400 cycles with synthesis and 250 in those without synthesis. And finally, using a failure load of 5744N, i.e., 80% of the maximum value, we obtained 2,259 cycles in the intact vertebrae as opposed to 200 in the group with synthesis and 170 in the group without synthesis.

When a failure load of 40% was applied there was no statistically significant difference in the number of cycles supported by the intact vertebrae and the with synthesis groups ($p=0.0542$). The intact vertebrae group supported a statistically higher number of cycles than the without synthesis group ($p=0.0064$), just as the vertebrae with synthesis supported a higher number of cycles than the vertebrae without synthesis ($p=0.0354$). This result indicates that the synthesis increased the resistance of the vertebra to levels similar to those of an intact vertebra. When a failure load of 60% was applied there was no statistically significant difference in the number of cycles supported by the intact and with synthesis groups ($p=0.0560$), nor was there for the groups with and without synthesis ($p=0.1051$). In addition, there was a statistically significant difference in the number of cycles supported by the intact and without synthesis vertebra groups. This result indicates that synthesis increased the resistance



SP: specimens, Post Ost. SP: fractured specimens in which osteosynthesis was performed; Fract. SP: untreated fractured specimens.

Figure 5. S-N curve, load in kN x number of cycles (x103), for the intact specimens and fractured specimens with and without synthesis.

of the vertebra to a level comparable to that of an intact vertebra (since there was no significant difference between the groups), but slightly lower (although there was no significant difference between the group with and the group without synthesis, there was a significant difference between the intact and without synthesis groups). With a 70% failure load there was a statistically significant difference in the number of cycles supported between all the groups of vertebrae. The intact group supported a significantly higher number of cycles than either the group with synthesis (p=0.0034) or the group without synthesis (p=0.0007), just as the group with synthesis supported a significantly higher number than the group without synthesis (p=0.0053). This result indicates that the synthesis increased the resistance of the fractured vertebra significantly, but not to levels comparable to those of intact vertebrae for this stress level. When a failure load of 80% was applied there was a statistically significant difference in the number of cycles supported by the intact vertebrae group when compared to the groups with (p=0.0098) and without (p=0.0071) synthesis. There was no statistically significant difference between the number of cycles supported by the with and without synthesis groups (p=0.6619) at this stress level. This result indicates that synthesis did not significantly increase the resistance of the fractured vertebra at high stress levels, and the resistance of the intact vertebra was significantly higher. The results of the statistical analysis are summarized in Table 1.

Table 1. Mean number of cycles of maximum compression resisted by the specimens analyzed by the different methods.

Group of Vertebrae	Mean Number of Cycles Supported (± Standard-Deviation)			
	FL[1] = 40% (2.9 (kN)	FL = 60% (4.3 (kN)	FL = 70% (5.0 (kN)	FL = 80% (5.7 kN)
Intact	81.8 (± 10.6)[a]	23.5 (± 9.9)[a]	15.6 (± 4.7)[a]	2.3 (± 0.4)[a]
With synthesis	42.1 (± 8.2)[a]	2.7 (± 0.1)[a b]	1.4 (± 0.3)[b]	0.2 (± 0.1)[b]
Without synthesis	2.0 (± 0.3)[b]	0.9 (± 0.4)[b]	0.3 (± 0.0)[c]	0.2 (± 0.0)[b]

[1]FL: Failure load. [a b c] Equal letters in the same column indicate values belonging to the same homogeneous group, in which no statistically significant difference between its components exists according to the Tukey test, with a confidence interval of 95%.

DISCUSSION

This study presents an evaluation of the behavior of coronal split fractures through fatigue tests for a new treatment method that includes a minimally invasive procedure. The treatment of thoracolumbar fractures still remains controversial with different forms of approach.[20] The classification proposed by Magerl et al.,[6] was an important tool to guide the evaluation and conduct of thoracolumbar fractures, stratifying them by trauma mechanism and osteoligament injury. Fractures classified as type A present an important crossroads for choosing which approach to take, i.e., breaking of the middle spine or rupture of the posterior wall. In coronal split fractures classified as A2, we have integrity of the middle spine, but because they are atypical fractures with cleavage in the coronal axis of the vertebral body, some peculiarities can make the treatment a challenge in certain cases because of invagination of the disc content, when interposed between the two bone fragments, due to the migration of the anterior fragment evolving into pseudoarthrosis of the fracture site. Davies et al.,[2] reported that coronal split fractures consolidate regardless of the type of treatment and pseudoarthrosis of the vertebral body is uncommon after conservative treatment. However, in fractures with significant diastasis at the focus a satisfactory union may not occur. Gaines et al.,[3] stated that in these cases consolidation will not occur without surgical treatment. The isolated posterior approach is recommended for thoracolumbar fractures by some authors,[21] while other authors opt for an isolated anterior approach.[22] We did not find a unanimous choice of the best therapeutic modality for treatment of A2 fractures in the literature, nor did we find a very expressive number of articles that address the topic. There is a considerable variety of techniques, conservative treatment with a rigid thoracolumbosacral orthosis (TLSO) or Jewett vest being one of the most used. Nonetheless, well-established bases are known for choosing an option in which stability criteria must be used in the treatment of spine fractures.[23] On the other hand, some authors opt for surgical treatment, either by arthrodesis with long or short segment. Hubner et al.,[24] published a study of the mechanical behavior of these fractures, considering that the first lumbar vertebra (L1) was fractured through different configurations of the fracture line. The authors discuss surgical and conservative treatment and show that coronal split fractures located in the anterior portion of the vertebral body are subject to fewer stresses and displacements, being more amenable to conservative treatment as compared to the fractures that occur in the middle of the vertebral body, corroborating with the model proposed by Denis et al.,[5] In this sense, we developed the minimally invasive percutaneous surgical procedure for these fractures in particular,[25] previously presented in another article in this journal. The present study continues in that line of research and demonstrates, through an experimental test, the ability of the synthesis material being tested to support fractures, resisting a higher number of cyclic loads than fractured vertebrae in which no synthesis was used, under the same biomechanical conditions. Thus, in the future the surgeon will be able to make a choice between surgical and conservative treatment, supported by these new therapeutic tools.

During the treatment of the fractures, orthoses (TLSO vests) can be used to contribute to its success, although we know that these orthoses do not immobilize 100% of the segment, justifying a minimally invasive osteosynthesis. The evolution of technology in the treatment of fractures through local reconstruction with osteosynthesis can preserve mobile segments and reduce surgical trauma and the complications of a larger procedure, in addition to reducing treatment costs.

According to Busscher et al.,[14] swine specimens come the closest to representing the human spine. The animals have similar biomechanical characteristics, which is important in the research of new implants and surgical procedures. The authors conducted studies and tests comparing load on segments of pig spine with segments from the spines of human cadaver. They also analyzed other literature that has proven the similarity between pig and human anatomy, especially in terms of joint size and orientation. They concluded that the swine spine can be a good model for biomechanical studies of the human spine. This encouraged our group to use the model for trials of the new technique,[25] this time considering fatigue in this experimental study (in a set of swine lumbar vertebrae), for ethical reasons and due to the difficulty of obtaining vertebrae from human cadavers.

Although there is a proportionally higher incidence of fractures in T12 and L1 in human beings,[4,5] we decided not to use the segment that contains these vertebrae. In this case, segments T12, L1 and L2 would be necessary, making the space for the handling and placement of the implants more difficult, given the size of the vertebrae. The vertebral bodies of the lower lumbar are larger, leading us to use this segment. In addition, the freezing of the anatomical pieces at -20ºC and subsequent thawing had no effect on the mechanical properties of the bones, intervertebral discs and ligaments, as demonstrated by Adams,[15] and this method was then used in the present study.

The analysis of the use of synthesis under the study conditions revealed a significant effect of exposure to the magnitude of the load on the number of cycles tolerated up until failure. It has been shown that synthesis increases the resistance of the fractured vertebra to levels equivalent to those of an intact vertebra depending on the stress level. As this was a study of non-human material, its applicability could be questioned. However, Thoreson et al.,[26] also demonstrated that the swine spine is a well-established experimental model for lumbar pathologies. The spine, however, is subject to loads in several planes: horizontal, vertical and rotational, and the biomechanical rigidity is less in compression-flexion tests as compared to pure axial compression tests.[27] In this study we present an innovative way to perform fixation of coronal split fractures, supported by prior studies.[24,25] The method can improve the rigidity of the system through restoration of the anterior spine, avoiding the removal of the fragments, the migration of the disc to the focus of the fracture and pseudoarthrosis.

We recognize that this study has some limitations, such as the fact that we only performed tests with pure axial load and with a reduced number of specimens in an animal model. Although this study has shown that using synthesis was superior in maintaining stability of the fracture and in preventing displacement for a greater number of cycles, it would not be possible to determine from this study alone whether the isolated use of this form would be reliable in the treatment of coronal split fractures. However, our group has researched these topics extensively over the last 10 years. We recently published other studies in this same journal that support the new technique, involving split type fractures and their biomechanical behavior,[24] in addition to having introduced this minimally invasive treatment more recently[25] in a study with other load conditions, demonstrating the viability of the proposed technique. We know that the in vivo environment is partially reproduced in the in vitro environment. However, under in vivo conditions the vertebrae gain resistance as the consolidation occurs, approximating the biomechanical conditions of intact vertebrae without running the risk of a distancing and subsequent pseudoarthrosis. The advantage of this technique is its being a minimally invasive method. New studies are underway to demonstrate the surgical technique and its in vivo behavior through new biomechanical analyses.

CONCLUSION

In this study we demonstrate the possibility of applying a minimally invasive technique for coronal split-type fractures through tests in swine model vertebrae. The synthesis material provides satisfactory fixation of the fracture line by means of focal compression, associated with the support of and resistance to cyclic axial loads.

All authors declare no potential conflict of interest related to this article.

CONTRIBUTION OF THE AUTHORS: Each author made significant individual contributions to this manuscript. ARH, CTS, ELAI and LFS were the main contributors to the writing of the manuscript. CLI, ELAI, FF, MR and LFS performed the procedures on the anatomical pieces and the laboratory assays and collected the data. ARH, CLI, ELAI, FF and LFS evaluated the statistical analysis data. All the authors worked on the bibliographical research, review of the manuscript and contributed to the intellectual concept of the study.

REFERENCES

1. Roy-Camille R, Lehèvre JF. Pseudarthrose des corps vertébraux du rachis dorso-lombaire. Rev Chir Orthop. 1975;61:249-57.
2. Davies WE, Morris JH, Hill V. An analysis of conservative (nonsurgical) management of thoracolumbar fratures and fractures-dislocations with neural damage. J Bone Joint Surg Am. 1980;62:1324-8.
3. Gaines RW, Humphreys WG. A plea for judgement in management of thoracolumbar fractures and fracture-dislocations. A reassessment of surgical indications. Clin Orthop. 1984;(189):36-41.
4. Singh K, Kim D, Vaccaro AR Thoracic and lumbar spinal injuries. In: Herkowitz HN, Garfin SR, Eismont FJ, Bell GR, Balderston RA (eds). Rothman–Simeone: the spine. Philadelphia: Saunders Elsevier; 2006. p. 1132-3.
5. Denis F, Armstrong GW, Searls K, Matta L. Acute thoracolumbar burst fractures in the absence of neurologic deficit: a comparison between operative and nonoperative treatment. Clin Orthop Relat Res. 1984;(189):142-9.
6. Magerl F, Aebi M, Gertzbein SD, Harms J, Nazarian S. A comprehensive classification of thoracic and lumbar injuries. Eur Spine J. 1994;3(4):184-201. doi: 10.1007/BF02221591.
7. Kim B-G, Dan J-M, Shin D-E. Treatment of thoracolumbar fracture. Asian Spine J. 2015;9(1):133-46. doi:10.4184/asj.2015.9.1.133.
8. **Azar FM, Canale ST, Beaty JH, Campbell WC. Campbell's operative orthopaedics, 13th Ed. London: Elsevier; 2016.**
9. Vaccaro AR, Kim DH, Brodke DS, Harris M, Chapman JR, Schildhauer T, Routt ML, Sasso RC. Diagnosis and management of thoracolumbar spine fractures. Instr Course Lect. 2004;53:359-373.
10. Tezer M, Erturer RE, Ozturk C, Ozturk I, Kuzgun U. Conservative treatment of fractures of the thoracolumbar spine. Int Orthop. 2005;29(2):78-82. doi: 10.1007/s00264-004-0619-1.
11. Butler JS, Walsh A, O'Byrne J. Functional outcome of burst fractures of the first lumbar vertebra managed surgically and conservatively. Int Orthop. 2005;29(1):51-4. doi: 10.1007/s00264-004-0602-x.
12. De Boeck H, Opdecam P. Split coronal fractures of the lumbar spine. Treatment by posterior internal fixation and transpedicular bone grafting. Int Orthop. 1999;23(2):87-90.
13. Khare S, Sharma V. Surgical outcome of posterior short segment transpedicle screw fixation for thoracolumbar fractures. J Orthop. 2013;10(4):162-7. doi: 10.1016/j.jor.2013.09.010.
14. Busscher I, Van Der Veen AJ, Van Dieën JH, Kingma I, Verkerke GJ, Veldhuizen AG. In Vitro Biomechanical Characteristics of the Spine: A Comparison Between Human and Porcine Spinal Segments. Spine (Phila Pa 1976). 2010;35(2):E35-42. doi: 10.1097/BRS.0b013e3181b21885.
15. Adams MA. Mechanical testing of the spine. An appraisal of methodology, results and conclusions. Spine (Phila Pa 1976). 1995;20(19):2151-6. doi: 10.1097/00007632-199510000-00015.
16. American Society for Testing and Materials. ASTM E9-89a. Standard Test Methods of Compression Testing of Metallic Materials at Room Temperature. 2000.
17. American Society for Testing and Materials. ASTM F1717. Standard Test Methods for Spinal Implant Constructs in a Vertebrectomy Model. 2009.
18. Parkinson RJ, Callaghan JP. The role of dynamic flexion in spine injury is altered by increasing dynamic load magnitude. Clin Biomechanics. 2009;24(2):148-54. doi: 10.1016/j.clinbiomech.2008.11.007.
19. Baranto A, Ekström L, Hellström M, Hansson HA, Swärd L. Vertebral fractures and separations of endplates after traumatic loading of adolescent porcine spines with experimentally-induced disc degeneration. Clin Biomechanics. 2005;20(10):1046-54. doi: 10.1016/j.clinbiomech.2005.06.014.
20. Mumford J, Weinstein JN, Spratt KF, Goel VK. Thoracolumbar burst fractures. The clinical efficacy and outcome of nonoperative management. Spine (Phila Pa 1976). 1993;18(8):955-70.
21. Levine AM, Edwards CC. Low lumbar burst fractures. Reduction and stabilization using the modular spine fixation system. Orthopedics. 1988;11(10):1427-32.
22. McAfee PC, Bohlman HH, Yuan HA. Anterior decompression of traumatic thoracolumbar fractures with incomplete neurological deficit using a retroperitoneal approach. J Bone Joint Surg Am. 1985;67(1):89-104.
23. Defino LHA, Fuentes AER, Remondi PH, Vallim EC. Tratamento conservador das fraturas da coluna toracolombar. Rev Bras Ortop. 2000;35(8):301-8.
24. **Hubner AR, Garcia MM, Maia RAV, Gasparin D, Israel CL, Spinelli LF. Comportamento mecânico das fraturas toracolombares do tipo split coronal: estudo por elementos finitos. Coluna/Columna. 2020;19(3):205-8. doi: 10.1590/s1808-185120201903223027.**
25. **Hubner AR, Luthi IF, Israel CL, Ribeiro M, Suarez ADH, Tagliari I, et al. Split type fractures of the spine: a new minimally invasive percutaneous technique. Coluna/Columna. 2021;20(1):55-9.**
26. **Thoreson O, Ekström L, Hansson H-A, Todd C, Witwit W, Aminoff AS, et al. The effect of repetitive flexion and extension fatigue loading on the young porcine lumbar spine, a feasibility study of MRI and histological analyses. J Exp Orthop. 2017;4(1):16. doi: 10.1186/s40634-017-0091-7.**
27. Haher TR, Tozzi JM, Lospinuso MF, Devlin V, O'Brien M, Tenant R, et al. The contribution of the three columns of the spine to spinal stability: a biomechanical model. Paraplegia. 1989;27(6):432-9. doi: 10.1038/sc.1989.69.