Research paper

A novel approach for biomechanical spine analysis: Mechanical response of vertebral bone augmentation by kyphoplasty to stabilise thoracolumbar burst fractures


aInstitut Pprime UPR 3346, CNRS – University of Poitiers – ISAE-ENSMA, France
bDepartment of Orthopaedic Surgery and Traumatology, University Hospital, Poitiers, France
cLaboratory of Anatomy, University of Poitiers, France
dMedtronic International Trading Sarl, Tolochenaz, Switzerland
eSpine-Neurostimulation Unit, N3 Lab, University Hospital, Poitiers, France

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A B S T R A C T

Kyphoplasty has been shown as a well-established technique for spinal injuries. This technique allows a vertebral bone augmentation with a reduction of morbidity and does not involve any adjacent segment immobilisation. There is a lack of biomechanical information resulting in major gaps of knowledge such as: the evaluation of the “quality” of stabilisation provided by kyphoplasty as a standalone procedure in case of unstable fracture. Our objective is to analyse biomechanical response of spine segments stabilised by Kyphoplasty and PMMA cement after experiencing burst fractures. Six fresh-frozen cadaveric spine specimens constituted by five vertebra (T11-L3) and four disks were tested. A specific loading setup has been developed to impose pure moments corresponding to loadings of flexion–extension, lateral bending and axial rotation. Tests were performed on each specimen in an intact state and post kyphoplasty following a burst fracture. Strain measurements and motion variations of spinal unit are measured by a 3D optical method. Strain measurements on vertebral bodies after kyphoplasty shows a great primary stabilisation. Comparisons of mobility and angles variations between the intact and post kyphoplasty states do not highlight significant difference. Percutaneous kyphoplasty offers a good primary stability in case of burst fracture. Kinematics analysis during physiological movements shows that this stabilisation solution preserve disk mobility in each adjacent spinal unit.

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Corresponding author. Tel.: +33 5 49 49 65 47; fax: +33 5 49 49 65 04.
E-mail address: arnaud.germaneau@univ-poitiers.fr (A. Germaneau).

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1. Introduction

Thoracolumbar burst fractures represent a significant part of spine injuries (Reitman, 2004), have a dramatic impact on patient social and professional activities (Bouyer et al., 2015) and induce sensible costs for our health care systems (van der Roer et al., 2005). More than 50% of these fractures concern L1 vertebra (Atlas et al., 1986) since this anatomical area constitutes a mechanical junction between the rigidity provided by the thoracic cage/ribs and the mobility provided by the lumbar spine (Wood et al., 2014). Aside from these major clinical repercussions, one can wonder if a biomechanical lesion surrounding at the thoracolombar junction has an impact on lumbar mobility and function.

A surgical treatment is required for most of these fractures to restore bone stability, prevent neurological deterioration and provide pain relief (An et al., 1992; Danisa et al., 1995; McEvoy and Bradford, 1985). Until now, spinal instrumentations have been considered as the gold standard to achieve these goals (Akahn et al., 1994; Carl et al., 1997, 1992; Chang, 1992; Esses et al., 1990; Garfin et al., 1985; McDonough et al., 2004) but several pitfalls need to be considered since the invasiveness of these techniques is far from neutral (Hakalo and Wronski, 2005; Scheer et al., 2015; Weyns et al., 1994). Kyphoplasty is a percutaneous surgical technique involving a balloon vertebral expansion followed by an injection of PMMA cement who has been developed and promoted more recently (Chen and Lee, 2004; De Falco et al., 2005; Hartmann et al., 2012; Olivier et al., 2007; Verlaan et al., 2005). This new minimally technique allows a vertebral bone augmentation with a reduction of morbidity (Maestretti et al., 2014; Saget et al., 2014), does not involve any adjacent segment (i.e. +1/−1 disk and vertebra) immobilisation and has been shown as a well-established technique for spinal injuries (Rahamimov et al., 2012). However, in contrast of encouraging clinical data, there is a lack of biomechanical information resulting in major gaps of knowledge such as: 1) How can we evaluate the “quality” of stabilisation provided by kyphoplasty, as a standalone procedure, in case of unstable fracture? 2) How to redistribute the mechanical fields on the adjacent disks and segments following local and regional strain changes? 3) How

Fig. 1 – Spine testing setup (a) and specimen with definition of local coordinate systems from marks (b).

Fig. 2 – Demonstrator model of spine with aluminium vertebrae and silicon disks (a) and stabilisation model with a screwed aluminium plate (b).
could be impacted the bone/cement interface at the level of the fracture on the long-term follow-up?

This aim of this paper is to present a biomechanical analysis of kyphoplasty in its main indication represented by burst fractures stabilisation and to address to the two first remaining questions. Kyphoplasty can be performed with different types of cements. Several works have been previously published concerning the clinical input regarding the appropriateness of using kyphoplasty as a standalone procedure (Acosta et al., 2005; Perry et al., 2005). It has also been shown that kyphoplasty, as a standalone procedure, using calcium phosphate cement does not insure a sufficient stability and needs to be associated with posterior instrumentation (Teyssédou et al., 2012; Wong et al., 2015). In contrast, from a clinical and radiological perspective, data show that kyphoplasty (standalone) using PMMA cement can be considered as an effective technique to regain the vertebral body height (Saget et al., 2014) and restore the spinal regional morphology. In this paper, we propose a biomechanical analysis of spinal specimens after a stabilisation by kyphoplasty using PMMA cement.

Based on all these considerations, an original approach using optical mark tracking method was developed and applied to a burst fracture model with pure moments to compare the range of motion (ROM) of the fractured and adjacent vertebrae before and after percutaneous stabilisation by kyphoplasty.

2. Materials and methods

2.1. Specimen preparation

For this biomechanical test procedure, 6 human fresh frozen specimens of 5 vertebrae (T11-L3) were used (3 female, 3 male, age: 76.5 ± 9.5 years) provided by the laboratory of anatomy of Poitiers Hospital. At harvest, the spines were dissected and soft tissues carefully removed to preserve bony parts and spinal ligaments. In accordance with the recommendations of Wilke et al. (1998), the specimens were stored at −28°C and thawed to room temperature before testing. For each specimen, the upper half of cranial (T11) and the lower half of the caudal (L3) vertebra were fixed in rigid polyurethane resin to apply loading. All spines were kept moist during the tests to retain the biomechanical behaviour of the specimens.

2.2. Spine testing setup

To reproduce physiological loadings on specimens, a specific spinal loading simulator (Fig. 1-a) has been developed for the purpose of this study, allowing spinal specimen to be tested in flexibility using pure moments according to one of the 3 physiological axes (sagittal, frontal or transverse).

The inferior vertebral body of the spine specimen was fixed. Pure moments were applied to the superior vertebral body by an electric servomotor able to reproduce flexion–extension and lateral bending movements. Torsional moments were imposed from a second electric servomotor placed in the according to the axial direction. Each load axis was equipped with a moment load cell to control imposed couple value.

Contrary to other spine testing setups (Wheeler et al., 2011), the superior vertebral body was allowed unconstrained movements in translations and in rotations excepted the axis of the imposed moment. During the loading, unconstrained movements were possible due to the compensation of the cranial weight of the setup by movable dead weights (Fig. 1). Free translations were guided by linear aerostatic bearings. Thus, there was no reaction force due to friction. As a result, imposed loadings were designed to correspond to pure spinal movements of flexion/extension, lateral bending or axial rotation. Values of moment were imposed alternatively and can go up ±7.5 Nm. These maximum loads should not involve irreversible defects on the specimens (Knop et al., 1997; Oxland et al., 1992; Panjabi et al., 1994; Vahldiek and Panjabi, 1998; Wilke et al., 2001a, 2001b).

2.3. Non-contact measurement method

A stereoscopic measurement system coupled with a 3D motion analysis method (3D mark tracking technique (Germaneau et al., 2010) was employed to measure the 6 motion components (3 displacements and 3 rotations). Then, angular changes of each vertebra due to loading were evaluated from three marks per vertebra (Fig. 1-b). As spine segments could move along the 3 planes and so to evaluate

![Fig. 3 – Axial views of CT images for the vertebral body of interest: (a) fractured and (b) post-kyphoplasty.](image-url)
the angles variations, range of motions (ROM) in terms of Euler angles were reported. Furthermore, from mark displacements, strain fields on vertebrae were calculated in order to evaluate primary stability offered by the stabilisation solution. Experimental tests showed that the measurement method is able to track accurate displacements up to 0.05 mm and rotations up to 0.1°.

2.4. Validation of the spine testing device

To validate the spine testing setup for biomechanical test on spine segments constituted by 5 or 7 units, it was necessary to verify that a pure moment was applied on each level. For this purpose, a demonstrator model of a spine was elaborated where 5 solids in aluminium modelled vertebral bodies linked by 4 disks made of silicon (Fig. 2-a). The upper and the lower aluminium solids were embedded in polyurethane resin to impose boundary conditions. An “experimental” stabilisation was simulated by using an aluminium fusion plate screwed between the second and the fourth solids in order (+1/-1 level compared to the level of further burst fracture simulation) to avoid any mobility around the central vertebra (Fig. 2-b).

Loadings of flexion/extension, lateral bending or axial rotation were imposed. Values of pure moment were imposed alternatively and could go up to ±2.5 N.m.

2.5. Experimental design

In a first step, specimens were tested “intact” (i.e. before any fracture simulation) by imposing loads of flexion/extension, lateral bending and axial rotation. Thus, for each specimen, native angular mobility between each vertebral body was determined (see Section 2.3). In the second step, a burst fracture (dynamic vertebral compression fracture) was generated on L1 on each specimen from a specific experimental protocol previously published (Germaneau et al., 2014) and using a Charpy pendulum. A systematic X-ray tomography confirmed that adjacent disks and ligaments were not injured and remained intact to match with the clinical considerations and practice: according to Magerl classification of thoracolumbar fracture used in daily practice (Fürderer et al., 2001; Magerl et al., 1994), if any disk or ligamentar associated lesion is evidenced, the clinical type of a suspected burst fracture (Type A) should be modified and switched to a Type B fracture. In this work, only fractures of Type A injuries (precisely Type A3.3) were studied.

Fig. 4 – Evolution of angle variations according to imposed moment for flexion–extension loading on a demonstrator spine specimen.
In the third step, each fracture was stabilised by stand-alone percutaneous balloon kyphoplasty. The material required includes a 20 cc Kyphon balloon from Medtronic for fracture reduction and PMMA cement to fill the cavity.

Generation of the burst fracture and adequate stabilisation were verified and validated by X-ray tomography images. Fig. 3 shows some examples of CT images of fractured and stabilized states of a vertebral body.

In the last step, stabilised specimens were tested in movements of flexion/extension, lateral bending and axial rotation.

For both test-steps, the specimens underwent two cycles of preconditioning of each imposed moment value (2.5, 5 and 7.5 Nm). Two principal effects linked to the stabilisation with cement were observed in this study: the primary stability of stabilised vertebra for flexion/extension movements and the angular mobility of stabilised specimen compared to the mobility measured on intact spine.

Analyses of variance were used to evaluate differences in the angle variations and in the strain measured on vertebral body between spinal segments. Non-parametric ANOVA (Kruskal–Wallis) and multiple comparisons testing (Dunn) were used to determine if there were any differences in strain and in angle variations between specimens. Non-parametric paired tests (Wilcoxon) were used to determine if there was any difference in angle variations between intact specimens and stabilised specimens. Non-parametric tests (Mann–Whitney) were used to test differences between flexion and extension in strain measured on vertebral body. All statistical analyses were done at a significance level of 0.05.

3. Results

3.1. Validation of the spine testing setup with synthetic specimen

Figs. 4–6 show angle variations measurements, performed on synthetic spine segment before and after stabilisation (stabilised systems with an aluminium plate). For non-stabilised cases, all the disks provide the same mechanical response. This confirms that pure moments were imposed uniformly along the segment and according to the three physiological axes. For stabilised cases, aluminium plate leads to disk immobilisation around the central vertebra (±1 level). Angle variations remain strictly similar as for intact specimens for all other analysed levels (and disks), showing here again that pure moment are imposed along all the parts of the specimen. These validation tests highlight the fact that the spine testing setup allows us to impose pure moment along the three directions without another reaction force.

Fig. 5 – Evolution of angle variations according to imposed moment for lateral bending loading on a demonstrator spine specimen.
3.2. **Primary stability offered by kyphoplasty**

Fig. 7 shows evolution of mean strain measured on vertebral bodies of L1 after stabilisation during the loadings and standard deviation calculated from the values measured on the six specimens. The higher strain values are observed for flexion-extension loadings, which directly involve traction or compression of vertebral body. For lateral bending and axial rotation loadings, the strain values are lower and more consistent across the loadings.

Fig. 6 – Evolution of angle variations according to imposed moment for axial rotation loading on a demonstrator spine specimen.

Fig. 7 – Evolution of strain of vertebral body of stabilised vertebra (L1) during tests of flexion/extension (a) and lateral bending and axial rotation (b) (mean curves and standard deviation error bars).
loadings, strain values remain lower than 0.02 (Fig. 7-b). Concerning flexion-extension (Fig. 7-a) values are more significant in compression involved by flexion loading compared to traction due to extension. Mean strain values remain low (up to 0.03) which shows that kyphoplasty offers an interesting solution for primary stability. After multiple comparison testings no significant difference regarding the biomechanical behaviour was found between spinal specimens (Kruskall-Wallis). Concerning the comparison of mechanical response according to the loading, no significant difference was found between flexion loading and extension loading (Mann-Whitney).

3.3. Angle variations

Figs. 8–10 show evolutions of mean values of angle variations on intact spine segments and after stabilisation. Error bars define response corridors. For flexion/extension loadings (Fig. 8), mechanical responses of spinal specimens after fracture in L1 and stabilisation are similar than responses before fracture (intact). Standard deviation values are particularly higher for the level L1/L2 which highlight a greater dispersion of mechanical response after fracture and stabilisation. For loadings of lateral bending (Fig. 9), responses are similar except for the level L1/L2 where angle variations are lower after stabilisation of the vertebra L1. Concerning loadings of axial rotation (Fig. 10), angle variations are lower than for the ones observed for the other loadings and similar mechanical responses are found between intact and stabilised specimens. Summations of angle variations between T11/L3 (Fig. 11) show that global rotations of spine segments are preserved after stabilisation of L1.

Fig. 12 summarises angle variations measured on intact and stabilised specimens for loadings of flexion, extension, lateral bending and axial rotation and for a pure moment of 5 N m. Angle variations are slightly higher (up to 1°) on disks around the fractured vertebra (L1/L2 and T12/L1) after stabilisation. No significant difference was evidenced between pre-fractured and post-kyphoplasty states (Wilcoxon’s tests) for the angle variations measured on each disk of each spinal segment.

Regarding the comparisons of angle variations between the different levels of spinal segments, Kruskall–Wallis testing demonstrated significant differences in the flexion angles between different levels of intact spinal segments. The follow-up of multiple comparisons testing (Dunn) showed that the mobility at L2/L3 level was significantly higher than at T11/T12. All other differences in flexion angle variations were not statistically significant. The same comment can be made for flexion loadings on stabilised segments: In this case, Kruskall-
Wallis testing demonstrated significant differences between the same levels at L2/L3 and T11/T12 and the multiple comparisons testing only highlighted a significant difference. As a result, stabilisation by kyphoplasty preserves the mobility at L2/L3 lumbar levels and around the fractured vertebra (L1/L2).

For extension loadings, Kruskall–Wallis testing did not demonstrate any significant difference in angle variations between different levels of intact spinal segments. However, after stabilisation Kruskall–Wallis testing demonstrated a significant difference in angle variations between the different levels. Dunn testing showed that angle variation of the level L1/L2 is significantly higher than the one of the level T11/T12. All others differences in angle variations were not statistically significant.

Concerning the loadings of lateral bending and axial rotation, Kruskall–Wallis testing did not show any significant difference in angle variation before fracture nor after stabilisation.

4. Discussion

4.1. Spine loading setup

A specific spine loading model has been developed for the purpose of this study to apply pure moment loading. Various apparatus have already been developed by the spine biomechanics community. One of the main difference between the various apparatus is the use of servohydraulic spinal loading fixtures to apply continuous pure moments versus cable-driven pure moment systems with stepwise unidirectional loading (Crawford et al., 1995; Eguizabal et al., 2010). Other systematic differences between the loading apparatuses included unconstrained linear slides versus load-feedback controlled slides, fixed ring versus sliding ring cable-pulley setups, and passive versus powered markers for three dimensional motion measurement. To allow free rotation and translation motions, pulleys and cables (Crawford et al., 1995; Crawford, 2011), cable-driven systems (Eguizabal et al., 2010; Tang et al., 2012) or actuators with sliding rails (Lysack et al., 2000; Yamamoto et al., 1989) were used. All these types of guidance systems may involve friction and force in reaction of free motion of the head of the specimen. One interesting originality provided by our testing device is to use non-contact guidance systems with aerostatic bearings which are frictionless by definition.

A study with comparison of four different apparatus has been performed by Wheeler et al. (2011) on seven fresh frozen lumbar segments (Wheeler et al., 2011). As a result of this study, no significant difference was evidenced in spite of
some variations of angle variations measurements. One limitation of the study of Wheeler et al. was the tests on only single lumbar motion segments.

To validate our spine simulator setup we chose to work with a demonstrator spinal segment constituted by four disks in order to avoid any variation due to donor variability and to insure repeatability of measurement validation tests. Our apparatus allowed us to impose pure moments on the whole height of the spinal segment and in particular on each intervertebral disk. It was also shown that even if one disk is blocked, the other disks continued to be subjected to the same pure moment loading.

One limitation of the present work is about the use of cadaveric specimens. This is a solution commonly used to test for implant testing. The novel spine simulator system presented in this paper represents an improvement to exert pure moments according to the three physiological directions.

4.2. Analysis of angle variations

Loadings imposed from pure moments and angle variations measured from a non-invasive method are comparable with loadings observed in a precedent study about a comparison of in vivo and in vitro loadings (Wilke et al., 2001a, 2001b). Furthermore, angle variations measured on the spinal specimens studied for this work are similar to the ones measured in previous in vitro studies (Kettler et al., 2007; Busscher et al., 2009). Concerning mobility analysis on our intact spinal segments, a significant difference for flexion loadings has been observed between the levels T11/T12 and L2/L3. This difference was not observed for the other loadings but is in conformity with anatomical geometry of vertebrae: orientations of facets of superior articular process are different according to frontal or sagittal views and for thoracic or lumbar levels. It is interesting to note that these observations are preserved after stabilisation by kyphoplasty standalone.

4.3. Clinical implication of standalone procedure vs circumferential stabilisation

Globally the same mobility was observed after fracture and stabilisation: there was no significant difference in angle variations on each disk of each spinal segment observed between before fracture and after stabilisation. However, we obtained a significant difference between the levels T11/T12 and L2/L3 on intact specimens as found again after stabilisation. Furthermore, a statistically difference appeared between levels for extension loading: angle variation of the level L1/L2

Fig. 10 – Angle variations for axial rotation loadings for intact and stabilised specimens (mean curves and standard deviation error bars).
is significantly greater after kyphoplasty than angle variation of the level T11/T12 which was not the case on intact specimens. Mobility has been increased in the disk between L1 and L2 because the impact to involve a burst fracture in L1. The prerequisite to consider the fracture into burst classification (Magerl, Vertebral Compression Fracture, type A) is based on the fact that axial compression involves lesion only on the vertebral body contrary to fractures classified type B or C where lesions of disks and ligaments are associated.

It is known that kyphoplasty allows the fusion of vertebral body but not the stabilisation of disks on either side of the fractured vertebra whereas we could suppose that a disk/ligament micro-lesion is often associated to the bone fracture. The observed statistically significant difference introduces the notion of a potential interest of a complementary fusion in addition of the stabilisation provided by kyphoplasty. The measurements of strain on consolidated vertebral bodies during loading showed that kyphoplasty insured a great primary stability. Strain measurement on the vertebral body during flexion-extension highlighted higher values for compression due to flexion loading compared to traction due to extension loading. Cement may adhere to trabecular bone porosities and stresses are well distributed for tension loading. Flexion loading involves compression and rigidity is not insured maybe due to osteoporosis of the specimens. This analysis would assume that kyphoplasty standalone provides an interesting primary stability from an intra-corporeal action. However, a strategy combining a complementary postero-lateral osteosynthesis could bring a stabilisation of ligament-disk structures. By considering a clinical point of view, in the case of burst fracture, we will recommend systematical NMR (Nuclear Magnetic Resonance) assessment of adjacent disks to perform a combined stabilisation.

5. Conclusion

Our results suggest that a percutaneous kyphoplasty offers a good primary stability in case of burst fracture. Interestingly, kinematics analysis during physiological movements showed that this stabilisation solution preserved disk mobility in each adjacent spinal unit. Our analysis highlights one limit of stabilisation by kyphoplasty standalone which is linked to potential lesions of adjacent disks or ligaments. However, in case of burst fracture, it could be reasonable to analyse morphologically adjacent disks by NMR in order to discuss of a combined stabilisation. Aside from pure anatomical considerations, further biomechanical studies comparing kyphoplasty alone vs combining kyphoplasty with posterior

![Fig. 11 - Global angle variations for T11/L3 (a) flexion/extension, (b) lateral bending, and (c) axial rotation (mean curves and standard deviation error bars).](image-url)
fusion in this indication would be helpful to find the best compromise in terms of efficacy/invasiveness for patients.

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REFERENCES


