The effect of CFR-PEEK cross-link in short fixation for the stabilization of lumbar metastasis: an in vitro comparative study

THE EFFECT OF CFR-PEEK CROSS-LINK IN SHORT FIXATION FOR THE STABILISATION OF LUMBAR METASTASIS: AN IN-VITRO COMPARATIVE STUDY.

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***Abstract*— The stabilisation of the spine after the orthopaedic management of vertebral bone metastasis is a crucial step for the success of the surgery. Carbon fiber reinforced PEEK (CFR-PEEK) is being widely adopted for fixation instruments thanks to its good biomechanical performances and radio transparency. The study investigates whether the integration of a CFR-PEEK cross link in a short fixation could become a viable alternative to long gold standard fixation. An experimental *in-vitro* study was then conducted, comparing different surgical CFR-PEEK stabilisations by characterizing their kinetic (i.e., Moment vs ROM curves and long-chain stiffness) and kinematic (i.e., segmental angular contribution) responses in flexion-extension, lateral bending and axial rotation. To provide additional insights on long-term applicability, the event of a pedicle screw loosening was also replicated. The experimental results suggest that a CFR-PEEK short fixation augmented with cross-link can be a promising conservative strategy. This unprecedent biomechanical quantitative comparison of CFR-PEEK stabilisations could support future clinical studies.**

Keywords* — spinal instrumentation, lumbar spine, CFR-PEEK, short fixation, short stabilisation, cross-link, vertebral metastasis, *in-vitro spine testing.

I. Introduction

VERTEBRAL metastases occur in more than the 5% of all patients with systemic cancer, and the lumbar segment is the most affected site of the spine [1]. In case of surgical treatment, spinal stabilisation plays a crucial role in the success of the intervention. Gold standard spinal stabilisation is established as a long posterior instrumentation fixing multiple spinal levels above and below the metastasis [2], [3]. However, this practice has proved many drawbacks in terms of high invasiveness, excessive adjacent-level overloading and mobility reduction. Recently, carbon fiber reinforced (CFR-) PEEK has been introduced in spinal fixation instrumentations in place of metallic alloys, integrating good biomechanical performances with radio transparency property (which is of particular interest in oncologic surgery) [4]-[6].

In order to reduce the number of fixed vertebrae and the corresponding large and severe side-effects of current lumbar metastasis stabilisation, this study explores the biomechanical effects of the combined use of CFR-PEEK cross-link and short fixation on the lumbar segment. Therefore, in the light of understanding the biomechanical applicability of this alternative, authors considered worthy to compare its kinematic and kinetic responses and those of the simple CFR-PEEK long and short fixations, with respect to control healthy and pathologic conditions and assess the effect of pedicle-screw loosening, which is the most common risks in short fixation. Hence, an experimental study was designed by recurring to a synthetic phantom loaded under flexion-extension, lateral bending and axial rotation. Hereby, this study presents for the first time a comparative biomechanical analysis of CFR-PEEK stabilisations for the management of lumbar vertebral metastasis and could support future clinical studies in oncological spinal surgery.

II. Materials and methods

A. Experimental setup

The study recurred to a Sawbones biomimetic phantom (SKU340) which replicated the lumbar segment and its adjacent vertebrae T12 and S1. The phantom presents all the passive elements of the spine, intervertebral discs, facet joints and the main ligaments (i.e., the anterior and posterior longitudinal ligaments, ligamenta flava, intertransverse ligaments, supraspinal and interspinal ligaments). The experimental set up is shown in Fig. 1. The phantom was disposed so as to have the L3 inferior endplate parallel to the global horizontal plane [7].

The loads were applied to the phantom through the linear-torsion test machine InstronE3000. The sacrum was always kept fixed to the machine and the loads were applied to the cranial vertebra through an already validated spine-loading apparatus [8]. In the case of axial rotation, the load was applied directly to the vertebra through a specific 3D printed coupling, while the bending along the sagittal and frontal planes were generated through an eccentric vertical load transmitted to the phantom through the combination of frictionless spherical and translational joints. In this latter case, the moment was calculated by assuming a constant arm with respect to the caudal constraint. Loads were applied in slow-rate displacement-control within small range of motion in order to prevent overloading. For sagittal and frontal bending, the linear displacement rate was set at 20 mm/min up to 10mm, whereas for axial rotation the angular rate was set at 0.5°/s up to 3°. Three replicas were performed for each test; the initial position was always set to guarantee a slight contact with the machine, without introducing any relevant initial pre-stressed condition. Finally, adhesive reflective markers were positioned on the vertebral bodies and on the transverse process, and their displacements were recorded through a marker tracking system, synchronous with the tests. Markers positions were then integrated with the load-displacement curve of the test machine to assess the applied moment generated at the S1 fixed joint.

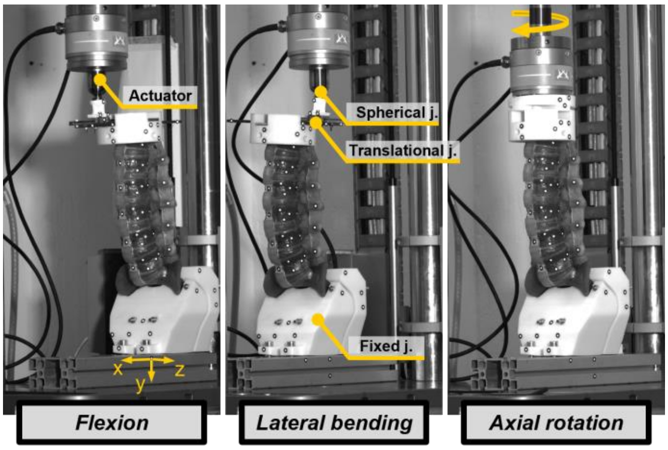

Fig. 1: The Sawbones mounted on the loading apparatus. The images are taken from one marker-tracking camera. The global reference system is also shown.

B. *Fixation layouts*

All the fixation layouts that were tested in this study were reproduced by experienced orthopaedic surgeons. The order followed to test the layouts was defined with the aim of minimizing the risk of phantom breakage (which did not occur). Hence, the tests started with the integral, non-instrumented phantom, considered as a 'healthy' control (*Ch*). Then, a metastatic lesion was mimicked in L3 by resecting the right half of its vertebral body. The posterior decompression performed surgically was also replicated by removing L3 pedicle and the posterior arch and taking care that no extra elements were affected. At that point, pedicle screws from Carboclear system (CarboFix Orthopaedic Ltd) were posteriorly inserted in L1, L2, L4 and L5 following anatomical trajectories. Dimensional consistency between pedicles and screws, as well as their mutual orientation, were confirmed by the surgeons by direct visualisation. From this condition, considered as a 'pathologic' control (*Cp*, Fig. 2), all the fixation layouts were tested: the long fixation (*L*, Fig. 2) was realised with bilateral CFR-PEEK rods connecting two spinal levels above and below the lesion in accordance with current clinical standard; the short fixation (*S*) connected only the spinal adjacent levels above and below L3, leaving L1 and L5 free to move. Then, a transversal rod-rod CFR-PEEK cross-link was added to the short fixation in correspondence of the metastasis, in a 'H' shape layout (*Scl*, Fig. 2). Finally, both short fixations were tested after the event of a pedicle screw loosening. When the screw anchorage in the vertebral bone fails, the load transmission through the screw between the vertebra and the rod is lost; a biomechanical equivalent mobilisation was replicated experimentally by disconnecting the right rod-screw joint above the lesion (*S-m* and *Scl-m*).

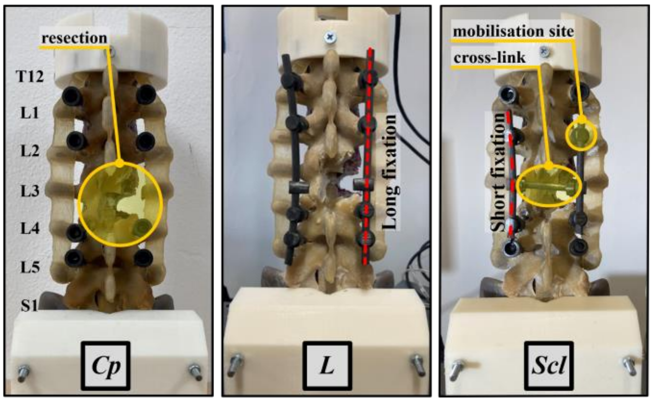

Fig. 2: Left - the Sawbones after the insertion of the pedicle screws, the reproduction of the posterior decompression and L3 vertebral body resection. Middle – Long fixation layout; the CFR-PEEK rods connect L1, L2, L4 and L5 vertebrae. Right: Short fixation layout with cross-link augmentation. The CFR-PEEK rods connect L2 and L4 vertebrae. The pedicle screw-rod joint detached to mimic the mobilization is also highlighted.

III. RESULTS

A. *Kinetic perspective*

Fig. 4 summarises the Moment-Range of Motion (RoM) behaviour of all the layouts in flexion/extension and lateral bending. To align the experimental curves and make them comparable, a preload of 0.4Nm was chosen. Overall, the 'pathologic' control always resulted more flexible than the 'healthy' one, and the implementation of any fixation offered a stiffening of the phantom. Both in flexion/extension and in lateral bending, short stabilisations (*S*, *Scl*) responses are positioned in-between the other curves, thus permitting both a less marked stiffening compared to the long stabilisation and the restoration of a more favourable mobility. In accordance with literature, along the sagittal plane, either cross-link augmentation or mobilisation influenced the short construct behaviour. As far as the investigated small loads are concerned, symmetrical behaviour in lateral bending is maintained in all short layouts. In lateral bending, cross-link addition enables a stiffened response at parity of load. In the range of ±5Nm, the total range of motion is reduced of the 10.8% with respect to the *S* layout. Moreover, cross-link also contributes to the stability preservation in the case of pedicle-screw loosening, since it holds back the drop of stability by half, from +27% (*S-m*) to +13% (*Scl-m*).

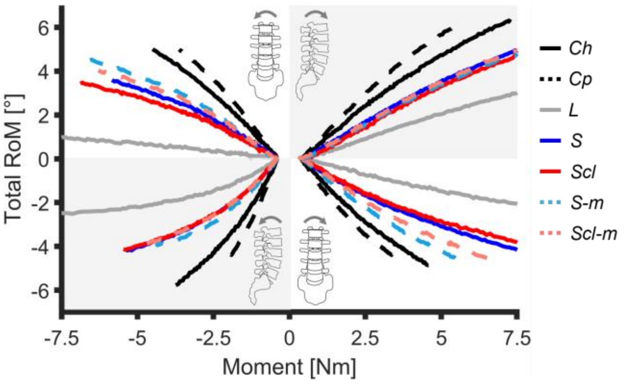

Fig. 3: Moment vs Total ROM curves of all the studied layouts. Mean values of the three replicas are represented. Each quadrant describes one different bending load: I and III flexion/extension; II and IV lateral bending on the resected and intact side, respectively.

In Fig. 4 is reported the torsional stiffness (K_T) calculated for each layout with a linear regression between the cranial vertebra rotation and the applied torque moment after having realigned the experimental curves at 0.6 Nm. The graph shows the results of all the constructs when rotated both on the intact and on the resected side. The symmetrical behaviour reported in the 'healthy' control is lost after the realisation of the resection. Interestingly, the 'pathological' control shows a stiffer response when rotated towards the resected side, with an unbalance magnitude ΔK_T of 0.19Nm, and a significant drop of the torsional stiffness with respect to *Ch*.
If the simple short fixation doesn't succeed in recovering this gap, the addition of the cross-link makes the short fixation comparable to the intact phantom like the long fixation. As a matter of fact, only these two layouts deviates less than the 8% from the values obtained by the *Ch*. The enhancement of cross-link augmentation in the short fixation is suggested also by the one-way ANOVA test which informs of a non-statistical difference between *S* and *Scl-m* layouts. That is to say that, in the case of pedicle screw loosening, if the simple short stabilisation becomes insufficient to guarantee an acceptable stability, on the other hand the addition of the crosslink makes the construct as stiff as the unimpaired short layout.

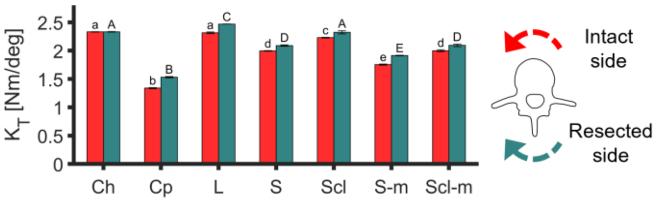

Fig. 4: Torsional stiffness of all the studied layouts. Labels indicate statistical significance among the stiffnesses along the intact (lower case labels) and resected (upper case labels) sides, according to Bonferroni post-hoc test.

B. *Kinematic perspective*

In order to quantify how the motion of vertebral joints across the lumbosacral segment varies with respect to the fixation layouts, the hybrid protocol [9] was adopted. The reference total RoM corresponded to the RoM achieved by the *Ch* layout under the following moments: 3Nm in flexion, 1.5Nm in extension, 1Nm in lateral bending. TABLE 1 describes the load necessary to reach the defined RoM, whereas Fig. 5 reports the motion contribution of each intervertebral joint, varying the type of fixation. Negative values correspond to registered discord rotations with respect to the imposed motions.

TABLE 1: Applied moment necessary for each configuration to achieve the same RoM obtained by the Ch layout at the indicated loads, in accordance with the hybrid protocol.

	Flexion	Extension	Lat. bending resected side	Lat. bending intact side
Ch	**3 Nm**	**1.5 Nm**	**1 Nm**	**1 Nm**
Cp	2.4 ± 0.05	1.2 ± 0.01	0.8 ± 0.02	0.9 ± 0.04
L	7.1 ±0.08	10.0 ± 0.09	3.0 ± 0.11	6.6 ± 0.70
S	4.1 ±0.09	2.5 ± 0.09	1.4 ± 0.09	1.4 ± 0.06
Scl	4.4 ±0.01	2.6 ±0.04	1.6 ± 0.10	1.6 ± 0.09
S-m	4.2 ±0.08	2.2 ± 0.10	1.2 ± 0.08	1.3 ± 0.05
Scl-m	4.1 ±0.07	2.5 ± 0.08	1.4 ± 0.07	1.3 ± 0.03

From a kinematic perspective, the introduction of the lesion mainly impacts on the joints below the lesioned vertebra (i.e., L3-L4 and L4-L5). Generally, the adjacent L3-L4 joint resulted less stiff, shielding the cranio-caudal motion distribution; for instance, in the case of flexion/extension L3-L4 contribution doubles, whereas L4-L5 one reduces from 20% to 3.2%. All the fixations (*L*, *S* and *Scl*) succeeded in stabilising the metastasis; nonetheless, the adjacent free joints motion is dependent on the fixation length: in the case of long fixation, L5-S1 is overinvolved with a bending contribution greater up to 5 times than the *Ch* layout response. Conversely, in short layouts, L1-L2 and L5-S1 share more than the 80% of the total ROM; interestingly, although L4-L5 is not involved in fixation, its contribution remains extremely small, i.e., flexion: 5.7±2.5%, extension: 3.0±1.3%, lateral bending on the resected side: 4.0±3.1%, lateral bending on the intact side: -1.9±2.9%. Finally, L2 pedicle screw loosening doesn't provide evident effects in the sagittal motion, while in lateral bending, a slight increased mobility is enregistered both at L2-L3 and at L3-L4 levels, revealing an increase of the relative rotations of the instrumented vertebrae and a reduced shielding effect on L4-L5 level.

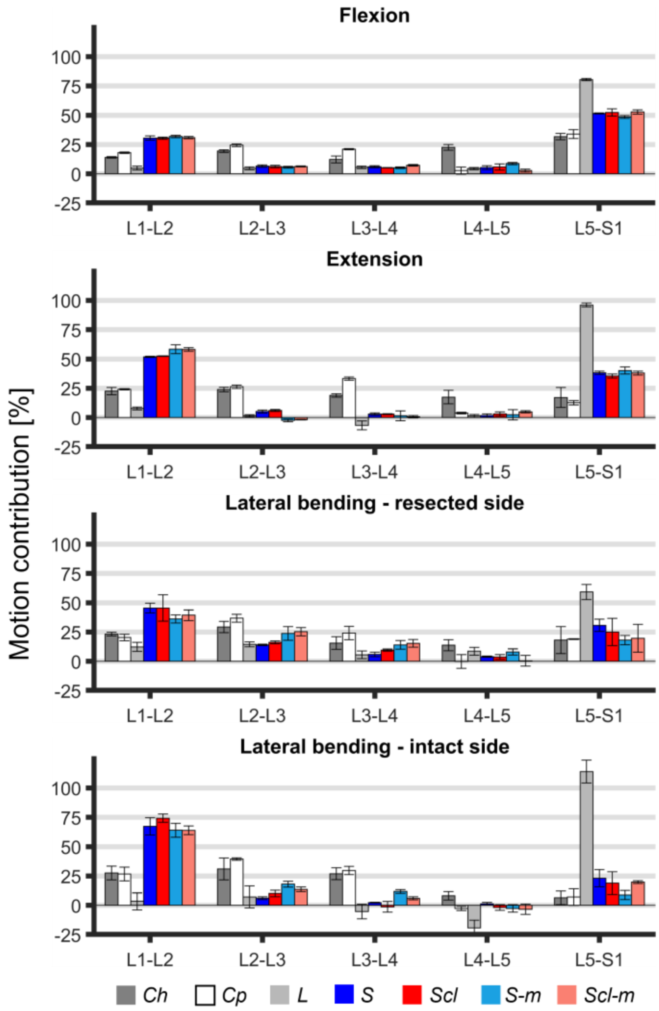

Fig. 5: Motion contribution of each vertebral joint, reported as percentage of the total L1-S1 range of motion.

IV. DISCUSSION

This *in vitro* study aimed to compare from a kinetic and kinematic perspective different CFR-PEEK stabilisation strategies and revealed that addition of a cross-link at the metastasis level could make short fixation a valid alternative.

Aware of the large spread of the use of synthetic phantoms in biomechanical studies [10], the authors recurred to a T12-S1 spinal segment Sawbones to conduct this study. Although this material doesn't replicate the diversity of real human specimen and didn't permit to consider the local mechanical properties of pathologic bones, the differences expressed in the study can only be attributed to the relative differences of the fixation layouts, without any hardly controllable contribution such as disc degradation or the heterogeneity among samples.

In accordance with the literature referred to metallic cross-link use [11]-[13], *Scl* response in flexion/extension resulted analogous with *S* layout, both in terms of long-chain stiffness and of segmental motion distribution pattern. Fig. 3 shows that cross-link in CFR-PEEK short fixation improves the frontal bending, by restoring a symmetrical behaviour on the two sides (thus, compensating the vertebral bone resection) and by limiting the effect of pedicle-screw loosening [14]. Fig. 4 puts light on the primary effect of cross-link in axial rotation. Indeed, if the K_T of simple short fixation is significantly reduced with respect to the 'healthy' control, the cross-link makes the construct comparable with long fixation and more conservative in terms of stability once mobilised. While rotating, the two longitudinal rods would get skewed, but the cross-link, that connects them transversally, counters this relative motion, making the whole construct stiffer.

Interestingly, Fig. 5 reports that in long fixation, vertebral levels below the resection had negative ROM contributions, that corresponded to vertebral rotations opposed to the main motion. These results suggest that the long fixation leads to local instabilities given by the altered distribution of the compressive loads and the over constrain of the construct [15]. The application of an eccentric load provoked a compressive stress state on the spinal segment, particularly for the long fixation where the secondary effect of the compression summed to the moment resulted more pronounced (being stiffer, a higher load was necessary to reach the same ROM at parity of arm, TABLE 1).

Although the experimental test did not plan the application of a pure moment, the recorded maximum linear force applied to the phantom resulted less than 100N (except for the *L* layout which reached ~220N): these magnitudes are consistent with the compressive loads applied in lumbar *in vitro* studies which range from 100N to 400N [16], [17].

Finally, since this study focused on the range of small displacements, eventual major deviations could have been resulted hided; however, the spinal stability is strictly correlated to the neutral posture [18], [19], and it is only in this range that the activation of muscles can be neglected.

V. CONCLUSION

To conclude, in the framework of oncologic surgery, this work compares CFR-PEEK posterior stabilisations by recurring to a biomimetic lumbosacral phantom. Particular attention was paid on the effect of cross-link augmentation on a less invasive short segment fixation. Results quantitatively demonstrated that short stabilisations permit a less marked stiffening compared to the long one, restoring a more favourable mobility and less unbalance responses among lumbar vertebral joints. The most imputed drawback to short stabilisations is the loss of stability in case of pedicle screw loosening which can put dramatically at risk the surgical outcome. The study highlighted that cross-link could limit this crucial aspect. The *Scl* layout proved to be a promising conservative strategy, worthy to be further investigated also in *in silico* modelling and to be considered in future clinical studies in the ambit of oncologic spinal surgery.

VI. ACKNOWLEDGMENT

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