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Posterior cervical spine crisscross fixation: Biomechanical evaluation

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Abstract

Background

Biomechanical/anatomic limitations may limit the successful implantation, maintenance, and risk acceptance of posterior cervical plate/rod fixation for one stage decompression-fusion. A method of posterior fixation (crisscross) that resolves biomechanical deficiencies of previous facet wiring techniques and not reliant upon screw implantation has been devised. The biomechanical performance of the new method of facet fixation was compared to the traditional lateral mass plate/screw fixation method.

Methods

Thirteen human cadaver spine segments (C2-T1) were tested under flexion-compression loading and four were evaluated additionally under pure-moment load. Preparations were evaluated in a sequence of surgical alterations with intact, laminectomy, lateral mass plate/screw fixation, and crisscross facet fixation using forces, displacements and kinematics.

Findings

Combined loading demonstrated significantly lower bending stiffness ($p < 0.05$) between laminectomy compared to crisscross and lateral mass plate/screw preparations. Crisscross fixation showed a comparative tendency for increased stiffness. The increased overall motion induced by laminectomy was resolved by both fixation techniques, with crisscross fixation demonstrating a comparatively more uniform change in segmental motions.

Interpretation

The crisscross technique of facet fixation offers immediate mechanical stability with resolution of increased flexural rotations induced by multi-level laminectomy. Many of the anatomic limitations and potentially deleterious variables that may be associated with multi-level screw fixation are not associated with facet wire passage, and the subsequent fixation using a pattern of wire connection crossing each facet joint exhibits a comparatively more uniform load distribution. Crisscross wire fixation is a valuable addition to the surgical armamentarium for extensive posterior cervical single-stage decompression-fixation.

Keywords

Posterior cervical internal fixation, Crisscross facet wiring, Lateral mass plate/screws, Segmental motion

1. Introduction

A number of early studies reported on the clinical outcomes and potential adverse consequences of multi-level laminectomy (Albert and Vacarro, 1998; Fairbank, 1971; Grubb et al., 1997). In 1995, we reported that multilevel cervical laminectomy induced biomechanical effects which could reduce the efficacy of the procedure (Cusick et al., 1995). These biomechanical findings contrasted the limited concerns expressed by contemporary “in vitro” laboratory studies that cervical laminectomy caused insignificant load-bearing or kinematic alterations (Ding et al., 1991; Goel et al., 1988; Zdeblick et al., 1992). Increasing clinical concerns regarding the potentially adverse effects of laminectomy, and our biomechanical findings, encouraged evaluation of techniques designed to offer a corresponding posterior fixation following multilevel laminectomy. At that time, however, such fixation was reliant on individual facet wires about a structural graft (Callahan et al., 1977; Garfin et al., 1988; Weis et al., 1996), and biomechanical evaluation of this technique was shown not only to fail to resolve the adverse effects of laminectomy but to exasperate many of the changes (Cusick et al., 1997).

These findings and concerns encouraged the development of a facet fixation system that could resolve these deficiencies and permit one-stage multilevel posterior cervical decompression and fixation fusion. The present study describes the biomechanical characteristics of the crisscross (CC) technique that resolves former limitations of facet fixation through a specific interconnection of individual facet wires securing of the facet joint. The biomechanical reliability of this method encouraged clinical implementation although ongoing, the technique application and long-term follow-up all supportive of the validity of the methodology.

Since this biomechanical evaluation and clinical applications, posterior fixation with screw systems mainly lateral mass plate/rod (LMPS) and pedicle screw (PS) have achieved increasing widespread acceptance for post laminectomy fixation (Anderson et al., 1991; Barrey et al., 2004; Deen et al., 2003; Fehlings et al., 1994; Kurz and Herkowitz, 1992; Xu et al., 2008). Certain biomechanical or anatomical limitations however, may restrict successful implementation maintenance or risk acceptance (Choueka et al., 1996; Coe et al., 1989; Deen et al., 2006; Inoue et al., 2012; Jones et al., 1997; Kast et al., 2006; Katonis et al., 2011; Kothe et al., 2004; Merola et al., 2002).

The hypothesis for this study is that the novel CC fixation technique that connects a specific sequence of individually positioned facet wires (cables) will resolve the biomechanical effects (strength and motion) induced by multilevel cervical laminectomy with comparable strength to lateral mass screw-plate constructs.

2. Methods

Thirteen unembalmed human cadaver spinal columns (C2 to T2), with care to preserve ligament components, were used in this study. Specimens were selected based on similar radiographic appearance. The mean age, height, and weight were 61 years, 170 cm, and 71 kg, respectively. Cervical columns were fixed superiorly and inferiorly allowing for motion segments from C3 to cervicothoracic junction to be included in this experimental model.

Retro-reflective targets were introduced into bony landmarks of each vertebra for obtaining overall and localized temporal kinematics. All 13 specimens were evaluated under complex loading (flexion-compression), and four of these specimens had additional evaluation using a pure-moment loading technique. This latter group of four also had inclusion of LMPS fixation as a component of the surgical alterations with the sequence consisting of intact, C4-C6 laminectomy, LMPS, and CC fixation. For the pure-moment loading, these specimens were mounted on a loading frame that included an inferiorly mounted six-axis load cell. The pure-moment load was applied using equal and opposite dead weights through cables and pulleys at the ends of a lever arm attached to the superior end of the preparation. The six-axis load cell fixed to the base of the preparation was used to monitor the loads such that adjustments to the pulley locations could be made to confirmed pure moments (Yoganandan et al., 2007). The specimens were tested under flexion and extension. Under each mode, pure moments were applied at 0.33, 0.5, 1.0, and 1.5 Nm levels. These load cycles were performed with data collection obtained on the third cycle.

To more closely replicate the clinical condition, complex loading studies were performed in all 13 specimens. A custom-designed fixture, described in a previous study, was attached to the proximal end of the specimens to apply flexion-compression loading while minimizing off-axis shear forces (Yoganandan et al., 1995). The force-deflection data from the piston load cell, the linear variable differential transformer, and the output generalized force histories from the distal six-axis load cell were recorded throughout the time of loading using a modular digital data acquisition system. The kinematic data were continuously recorded using a video motion analyzer. The strength data from the load cell and the force gauge were synchronized with the kinematic data using a single trigger. Force-time and deflection-time traces from the piston sensors were transformed into a force-deflection curve for analysis of stiffness. Stiffness of the structure was defined as the slope of the force-deflection curve in its most linear phase.

Localized kinematics of the structure were derived from: three targets inserted into each vertebra for kinematic analysis. The position of each vertebra (considered as a rigid body) was recorded at each load step using a 3-D motion tracking system (Motion Analysis Corp., Santa Rosa, CA USA). Spinal kinematic responses were obtained as angular rotations in the sagittal plane. Rotational measures under load were derived for each spinal level and expressed as angular motion with respect to the unloaded state.

Biomechanical responses were recorded using pure moment in 4 of 13 specimens and complex loading studies in all 13 specimens. A three-level laminectomy with attention to maintaining facet integrity was performed. Specimens were loaded using the previously described methods. In the four specimens where both pure moment and complex loading was done, the pure moment test was done before the complex loading for each surgically-altered configuration. The same four specimens also underwent LMPS fixation with a small notched plate-screw set (DePuy Synthes Inc., Raynham MA, USA). Lateral mass screws were inserted after defining the facet line and lateral aspect of the lateral mass. All screw holes were drilled with a 2.0 bit and after measuring the appropriate plate 3.5 mm titanium cortical bone screws to achieve bicortical fixation. These specimens were again loaded using the same parameters.

All 13 specimens, including the four LMPS preparations, underwent facet fixation using the CC technique. This technique, which will be described in greater detail in discussion of clinical applications, consists of interconnections of individual components of the commercial Sof-wire cable system (DePuy Spine Inc., Raynham MA, USA) passed through drill holes in the superior aspect of the inferior facet. The 20-gauge cables were secured in a cinch and crimp technique with labeling of wires in a sequential rostral-caudal pattern (Fig. 1). The sequence of cable connection in this experimental model is cable 1 to 3; cable 2 to 5; and cable 4 to 6. The lower cable is passed around the spinous process below the caudal level of the laminectomy before being crimped to cable 4. Except for the lower connection, all other connections can be crimped before final tightening. Tightening at the lowest level secures connections across all the facet joints and is secured with double-crimp placement (Fig. 1).

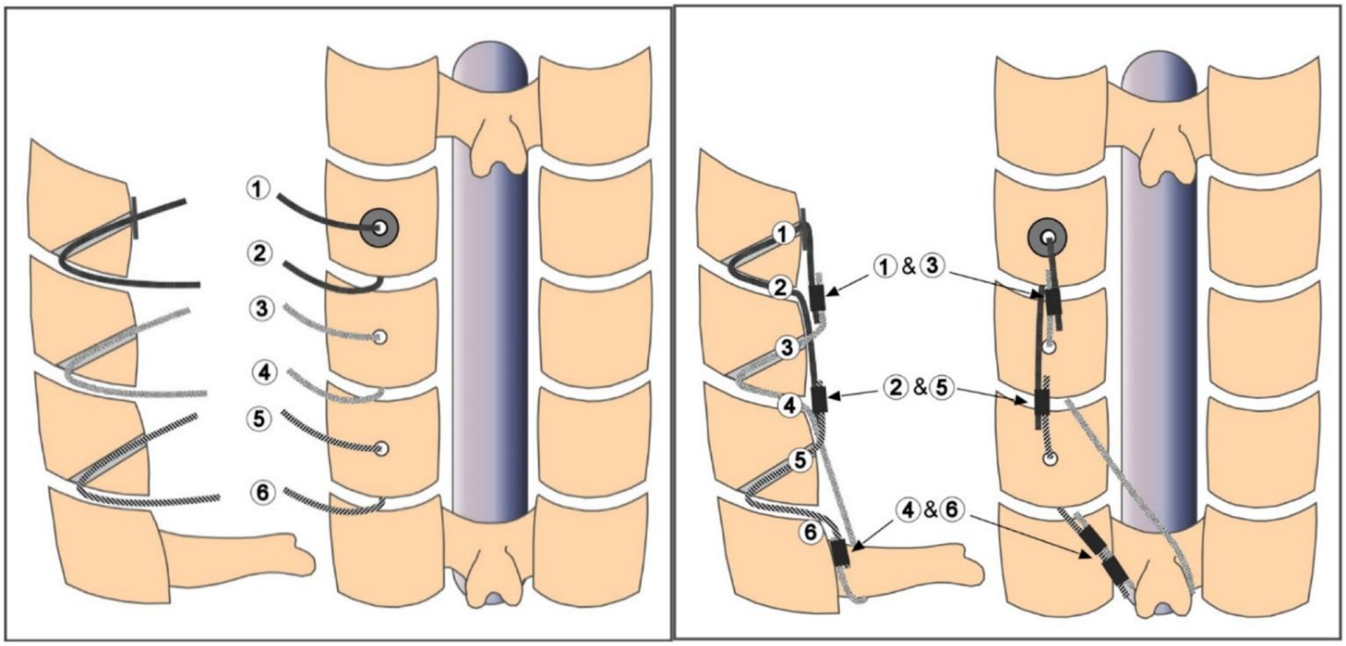


Fig. 1. Illustrations in the three-level laminectomy preparation demonstrating the sequence of cable interconnections necessary to achieve facet fixation by crossing each facet joint. The last cable encircles the inferior spinous process (cable 1 to 3; 2 to 5; and 4 to 6). The stress points at the proximal and distal connections are mitigated by inclusion of a small button and double crimps, respectively, performed in a bilateral manner.

Statistical analysis was done comparing biomechanical measures including stiffness and rotational motions. Surgical procedures were quantitatively compared by using repeated measures analysis of variance (ANOVA) with post-hoc Fisher PLSD test with a significance of $p < 0.05$.

3. Results

The biomechanical data for complex loading were collected for 13 intact, laminectomized, and CC fixation specimens and four LMPS fixation specimens. Pure-moment loading was evaluated in four specimens in intact, laminectomized, LMPS, and CC preparations. In this latter group, LMPS fixation was performed before CC fixation, creating the “worst-case” comparative scenario of specimen integrity for CC fixation. The expected reduction of acute mechanical stability and strength induced by multi-level laminectomy was verified in the present study, and the decreased mean stiffness and increased motion incurred by laminectomy was reversed by CC fixation under combined loading (Fig. 2).

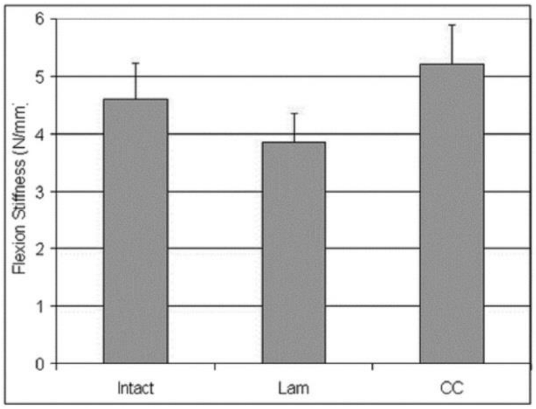
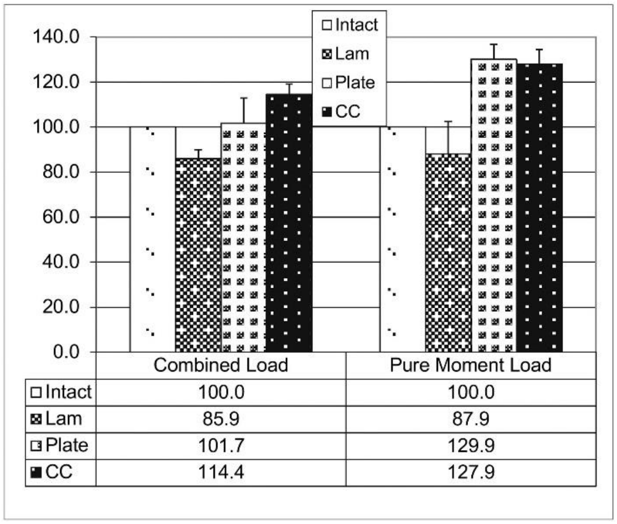


Fig. 2. Comparison of the compression-flexion column stiffness (N/mm) of intact (INT), laminectomized (LAM), and crisscross (CC) fixation. Decreased mean stiffness induced by laminectomy was reversed by CC fixation.

Stiffness and motion data were normalized with respect to intact on a specimen-by-specimen basis. Statistical analysis comparing intact preparations to laminectomy and surgical procedures resulted in the following. For both combined flexion-compression, and pure-moment loading, the inclusion of LMPS preparations demonstrated that bending stiffness was significantly lower ($p < 0.05$) between laminectomy and both CC and LMPS preparations (Fig. 3). Although no significant differences were noted between the two construct configurations (Fig. 4), CC fixation demonstrated a comparative tendency for increased stiffness with combined versus pure-moment loading (Fig. 3). Crisscross fixation, therefore, demonstrated consistent increased stiffness under both types of loading, whereas LMPS was significantly stiffer than intact only under pure-moment loading (Fig. 3).



	Combined Load	Pure Moment Load
□Intact	100.0	100.0
⊠Lam	85.9	87.9
□Plate	101.7	129.9
■CC	114.4	127.9

Fig. 3. Comparison of the normalized flexion stiffness of laminectomized (LAM), crisscross (CC), and lateral mass plate/screw (LMPS) fixation with respect to intact (INT) preparations during combined and pure-moment load application. Average stiffness values expressed as a percentage of the intact specimen. Percentages were determined on a specimen-by-specimen basis. Both fixation techniques showed restoration of stiffness to intact ($p < 0.05$). A non-significant but comparative tendency was noted for CC fixation to demonstrate a more consistent stiffness under both types of loading with LMPS being significantly stiffer than intact only during pure-moment loading.

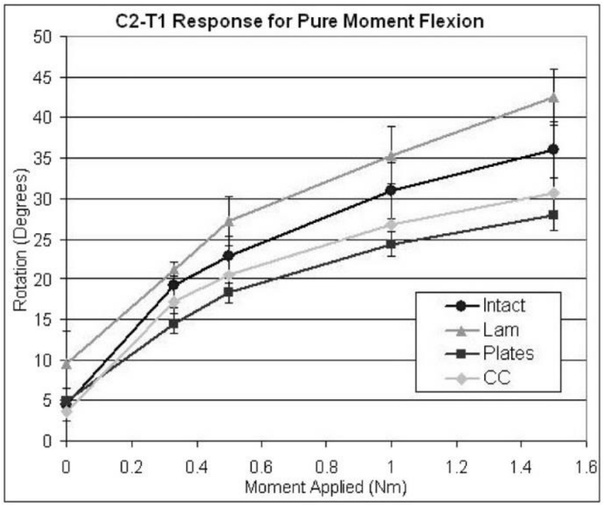


Fig. 4. Average flexion responses in the intact, laminectomized (LAM), crisscross (CC) fixation, and lateral mass plate/screw (LMPS) fixation. Crisscross fixation was conducted after plate removal. Crisscross and LMPS fixations caused a decrease in average motion relative to intact levels.

Laminectomy caused an increase in overall sagittal rotation angle with changes of greater magnitude at the upper level (C3) associated with rostral-to-caudal decrease. CC and LMPS fixations both caused a decrease in overall motion above intact levels ($p < 0.05$) (Fig. 5, Table 1). The increased motion at rostral levels persisted with both constructs (CC and LMPS) with CC fixation demonstrating more uniform changes in segmental motion.

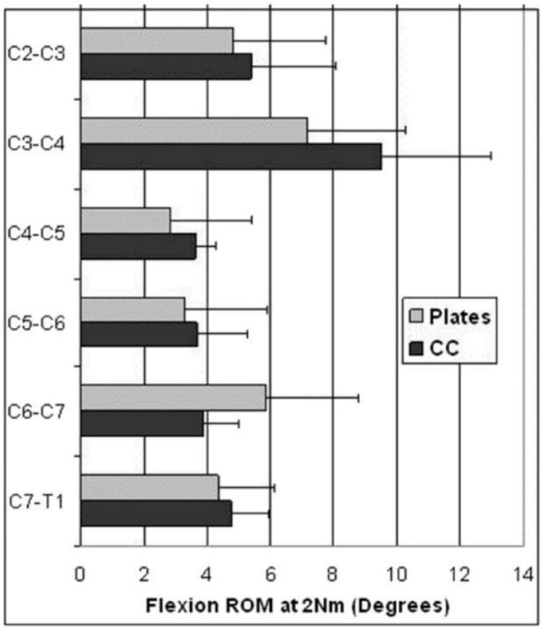


Fig. 5. Comparison of flexion responses on a level-by-level basis with CC and LMPS fixation, with CC fixation demonstrating more uniform rostral-to-caudal changes.

Table 1. Flexion and Extension stiffness of C2-T1 specimens under pure-moment and combined loading.

Test Condition	**Flexion pure-moment load**	**Flexion combined loading**	**Extension pure-moment load**	**Extension combined loading**
	Mean (SErr) (Nm/deg)	**Mean (SErr) (N/mm)**	**Mean (SErr) (Nm/deg)**	**Mean (SErr) (N/mm)**
Intact	0.068 (0.006)	3.13 (0.37)	0.095 (0.004)	1.96 (0.19)
Laminectomy	0.058 (0.007)	2.49 (0.11)	0.097 (0.007)	1.89 (0.16)
Facet plating	0.089 (0.009)	3.07 (0.10)	0.137 (0.018)	2.76 (0.17)
Crisscross	0.086 (0.004)	3.30 (0.12)	0.097 (0.005)	1.84 (0.05)

4. Discussion

The biomechanical data indicate that the CC method of posterior cervical wiring is an effective procedure to achieve rigid internal fixation. This method, following multi-level laminectomy, restores strength and overall motions to levels approaching intact preparations during flexion-compression testing (Fig. 3). Flexion-compression are the principle responsible modes of force application in the causation of curvature alterations following multi-level laminectomy (Abumi et al., 1999; Albert and Vacarro, 1998; Cooper et al., 1988; Maurer et al., 1991; Mihara et al., 2001; Nazarian and Louis, 1991; Swank et al., 1997; Yoganandan et al., 1995). Improved stability during this mode of force application decreases concerns of subsequent adverse alignment or curvature changes. The uniform reduction of these flexural distortions with CC fixation are further assisted by the morphology of the facet joints producing an extension-compression alignment which may further alleviate the increased sagittal rotations induced by flexion-compression loading.

In conjunction with complex loading studies, specimens were also tested using the pure-moment technique. Extension studies with this latter testing demonstrated the expected comparative increased stiffness and decreased motion with LMPS. This significant difference compared to flexion loading most likely represents a buttress effect and increased local rigidity induced by the plate/screw construct. The flexion testing with pure-moment application, however, did not demonstrate any significant differences between CC and LMPS with both constructs restoring strength to levels slightly above intact (Fig. 4). Biomechanical behavior was similar for both constructs during pure-moment loading, and under the conditions of increased flexural rotations with combined loading. During combined loading, CC fixation demonstrated a performance equal or improved compared to LMPS specimens (Fig. 5). This pattern of load acceptance during the complex loading studies, including compression application, suggests improved general stiffening with CC fixation as compared to relatively greater local stiffening with LMPS fixation. This latter finding probably represents a greater stress shielding, whereas CC fixation allows a comparatively more uniform stress sharing. The greater generalized load distribution along the column with CC fixation suggests a more dynamic and physiologic character of force application with a relative distribution of forces acting upon neighboring levels. Although the majority of biomechanical evaluations of cervical spine constructs have been tested in pure-moment loading, the present study indicates that the compressive vector puts more demand on the construct than just the pure-bending mode.

The greater stiffness and decreased motion in extension and the relatively increased local strength in flexion-compression with LMPS suggest that this method may impart greater stresses on neighboring levels compared to CC fixation. Although the clinical impact of these stresses on adjoining segments remains conjectural, the comparative changes with CC fixation may offer a long-term theoretical advantage of reducing the acceleration of such degenerative changes. The more uniform segmental motion changes during flexion-compression loading tend to support this advantage.

Certain technical points in this study may influence the biomechanical comparison of CC and LMPS fixation. Although screw size can influence pull-out resistance, the use of the 3.5-mm cortical screw has been proposed (Cooper et al., 1988; Nakashima et al., 2012; Swank et al., 1997) as the appropriate compromise choice for lateral mass implantation. It is feasible, therefore, that the comparative trend of LMPS fixation to offer less resistance in flexural rotations than CC fixation may relate to the possible inconsistent achievement of bi-cortical purchase. In applying the CC technique, consistent bi-cortical positioning is achieved without concerns that may be applicable to lateral mass screw constructs. Although cancellous bony contact is small with CC fixation, the pull-out resistance throughout the cervical column is more consistent and predictable. Pull-out strength for lateral mass screws has been shown to be dependent upon vertebral level with the greatest pull-out strength at C4 and a decrease at C2 and C7 where the lateral masses are of smaller size (Coe et al., 1989; Cooper et al., 1988; Deen et al., 2003; Inoue et al., 2012). Long LMPS constructs, especially at lower cervical levels where these relatively smaller lateral masses associated with a greater moment arm at the distal portion of the fixation plate, have increased potential for screw loosening or avulsion. In accomplishing lateral mass fixation, the use of a screw-rod system may offer some advantages over the screw-plate construct, including improved contouring, more precise screw placement, and possibly greater strength during flexural loads (Swank et al., 1997). These advantages, however, are more evident in the operative setting rather than laboratory applications of these constructs which is not limited by exposure or anatomic variations. In this regards, the use of small-notched plates shares the characteristic with screw-rod constructs of being a relatively constrained system with expectations of similar rigidity. In contrast, CC fixation encounters less vertebral level variability with more uniform multi-level fixation strength and is relatively impervious to curvature deformities.

These considerations may be extended to evaluating the comparative effectiveness of the screw-plate/rod and crisscross system. In this regards, Schmidt et al., propose certain factors that determine the stability of posterior cervical fixation system (Schmidt et al., 2005). First, the interface of bone with the specific fixation devices will differ relative to the character of the bone stock. The screw bone interface usually consists of unicortical purchased with a more extensive cancelous bone contact whereas the cable fixation offers a consistent bicortical purchase. The differing material properties between the two tested systems suggest a greater deformation under induced moments with the cable fixation relative to the more rigid screw-notched plate system and the crisscross system can be considered to be less constrained than the notched plate construct. The increased stability anticipated by the constrained system to actively applied forces was not verified in the present study. The crisscross technique, therefore, maintains sufficient axial load stability to maintain alignment. Additionally, the use of the cable fixation technique offers comparable reduced availability and cost implementation.

Regarding potential clinical applications, because of the surgical techniques involved, CC fixation may be thought of as a safe and effective technique, however may appear relatively complex. Compared to surgical implementation of screw-plate fixation, CC wire fixation requires about the same operating time and blood loss is similar. The evolution of this technique involved a laboratory trial of noncontiguous facet connections that crossed each facet joint. It was discovered that this sequence of wire connections offered restoration of rigidity as well as the fortuitous “tightening” of the entire construct with a single tension application at the distal connection. The consideration of bone quality is a concern with all forms of fixation. CC fixation, however, in contrast to most lateral mass screw procedures, achieves consistent bicortical fixation with minimal cancellous bone involvement. Along with the more uniform force distribution offered by CC fixation, the character of fixation suggests that this technique may be preferable in subjects with suspect bone quality. In this respect, CC fixation offers promise as a salvage procedure.

5. Conclusions

The CC technique offers the biomechanical advantages of immediate mechanical stability of the cervical spinal column with resolution of the potentially deleterious effects of excessive flexural rotations following multi-level laminectomy. The potential inconsistencies and anatomic limitations induced by screw penetration and orientation are not associated with facet wire passage, and the subsequent fixation exhibits a more generalized load application along the cervical column. These considerations suggest that CC fixation is a valuable addition in the surgical armamentarium for accomplishing extensive (C2-T1) posterior cervical single-stage decompression-fixation procedures.

Disclosure

Conflicts of interest: None.

Acknowledgement

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