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ORIGINAL ARTICLE

The mechanism in junctional failure of thoraco-lumbar fusions. Part I: Biomechanical analysis of mechanisms responsible of vertebral overstress and description of the cervical inclination angle (CIA)

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Abstract

Purpose The purpose of the study is to describe the biomechanical theory explaining junctional breakdowns in thoraco-lumbar fusions, by taking the example of vertebral compression fractures. Also, a new angle, the cervical inclination angle (CIA), describing the relative position of the head at each vertebral level, is presented.

Methods For the CIA, the data were collected from 137 asymptomatic subjects of a prospective database, containing clinical and radiologic informations. All the 137 subjects have an Oswestry score less than 15% and a pain score less than 2/10 and were part of a previously published study describing the Odontoïd-hip axis angle (ODHA). For each vertebral level from T1 to T12, the CIA as well as the vertical and horizontal distances was measured in reference to the sella turcica (ST), and a vertical line drawn from the ST. Average values and correlation coefficients were calculated.

Results The CIA is an angle whose average value varies very little between T1 and T5 (74.9°–76.85°), and then increases progressively from T6 to T12. T1–T5 vertebra are always in line within the thoracic spine for each subject and can be considered as a straight T1–T5 segment. In addition, it was found that the vertical inclination of T1–T5 segment is correlated with the C7 slope ($R^2 = 0.6383$).

Conclusion The T1–T5 segment inclination is correlated with the C7 slope, and because the latter defines the cervical curve as previously shown, the T1–T5 segment can be considered as the base from which the cervical spine originates. Its role is, thus, similar to the pelvis and its sacral slope, which is the base from which the lumbar spine originates. The CIA along with the ODHA, which describes the adequacy of the global balance in young and elderly asymptomatic populations, are two important parameters that could help us to better understand junctional breakdowns in thoraco-lumbar fusion surgeries.

Keywords Proximal junctional kyphosis · Proximal junctional failure · Bending moment · Vertebral fracture · Sagittal balance

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Introduction

Junctional kyphosis (JK) or failure (JF) can be defined as an abnormal change in the degree of kyphosis, or angulation, than that seen in the early post-operative period, from either failure of the vertebrae, the soft tissues or the bone–implant interface in thoraco-lumbar fusion surgery. The complication can take place at the proximal or distal end of the construct [1]. In most cases, it is the proximal form, which is observed (PJK: proximal junctional kyphosis, or PJF: proximal junctional failure).

PJK is a radiographic finding and is defined as a proximal junctional sagittal Cobb angle (PJA) between upper instrumented vertebra (UIV) and two levels above the UIV, greater than 10° or at least 10° greater than the corresponding preoperative measurement [1–3].

PJK or PJF can occur early, during the postoperative period (up to 12 weeks post-op) or more progressively during months or even years [4]. Incidence of PJK/PJF varies widely in the literature with authors reporting rates ranging from 17 to 61%, due to different definitions and study designs [2].

PJF has been defined as a symptomatic form of PJK surgery and with an increased PJA greater than 15°, possibly needing revision [5].

As reported by Hostin et al., fracture is the most common PJF mode (47%), followed by soft-tissue failure (44%), screw pullout and trauma [6]. However, there is evidence that the mode of failure depends on the location of UIV. More fractures are seen in thoracolumbar failures in contrast with upper thoracic failures, which are more frequently seen as soft-tissue failure and compression fractures of various degrees [6].

Clinically, PJF manifests with pain, neurological deficit, gait difficulties, sagittal imbalance and social isolation [7].

In general, PJF requires revision surgery. Treatment depends on the flexibility of the spine. For a flexible and harmonious kyphotic spine, extension of the instrumentation to the next stable level, alone or associated with a Smith Peterson osteotomy (SPO) can be recommended. For a rigid spine containing ankylosing lesions, flat back sequelae, or with localized angular kyphosis, extension of instrumentation may have to be combined with a three-column osteotomy such as Pedicle Subtraction osteotomy (PSO) to correct spinal deformity, pain and neurological deficit [1, 4, 8].

Reports on the prevalence, outcomes, possible risk factors, and prevention of PJK in adult spinal deformity surgery have already been attempted. However, available data remain controversial and pathogenesis of the complication not fully understood [7]. For this reason, it is difficult to anticipate this complication.

From this background analysis, we conclude that current status of the literature reflects the misunderstanding of the exact patho-mechanism of junctional failure.

As mentioned above, junctional kyphosis can present as two major modes [6]: vertebral fractures and soft-tissue failure. When it manifests mainly as soft tissue failure, the etiology is certainly to be found in the deleterious effect of surgical approaches on adjacent levels such as facet joint injury, inter- and supra-spinous ligaments tears, muscle detachment and other anatomical damage [1, 2, 4–7, 9–27]. This is clearly understandable and supports the fact that extensive surgical approaches should be avoided, although in some cases, there can also be genuine failure through uninjured soft tissue. In some cases, the aging-related muscular degeneration or the neuromuscular dysfunction seen in Parkinson's disease or camptocormia (bent spine syndrome) can explain the progressive weakening of the posterior tension band, generating overload of the anterior column. In this case, there is a risk of vertebral fracture. When presenting as a fracture, the mechanism of failure is similar to compression fractures. This is further explained here below.

Biomechanics of vertebral compression fractures

Junctional failures are clearly the result of an imbalance between anterior column compression forces and posterior column tension band strength. In other words, there is an excessive bending moment, a mechanism very similar to what is seen in vertebral compression fracture (VCF), a common pathology of the elderly population. VCF can occur after minor trauma or even fortuitously discovered on systematic X-rays. It has been shown that kyphotic patients have higher risk of VCF than the normal population [28].

Alf Nachemson and other authors previously reported that a lumbar functional spinal unit (SFU) can support a maximum axial weight of 500 kg, but a bending moment of only 20 Nm in flexion [29, 30]. Consequently, if the lever arm length is increased by only 10 cm, the maximal weight supported by the SFU will be reduced to 20 kg [30]. It is, thus, important to restore the anterior wall height of a fractured vertebra, to prevent the risk of additional adjacent fractures or domino effect (DE) [31] (Fig. 1). Disc height loss due to degeneration at several levels increases thoracic kyphosis and results in a similar biomechanical condition for the upper adjacent vertebra than a VCF.

The biomechanical consequence of an increased thoracic kyphosis is an anterior trunk shift (TS), anteriorly shifting the center of gravity, leading to a domino effect (DE), further increasing the kyphosis [31]. This has been observed in the older study group of asymptomatic patients describing the ODHA angle [32].

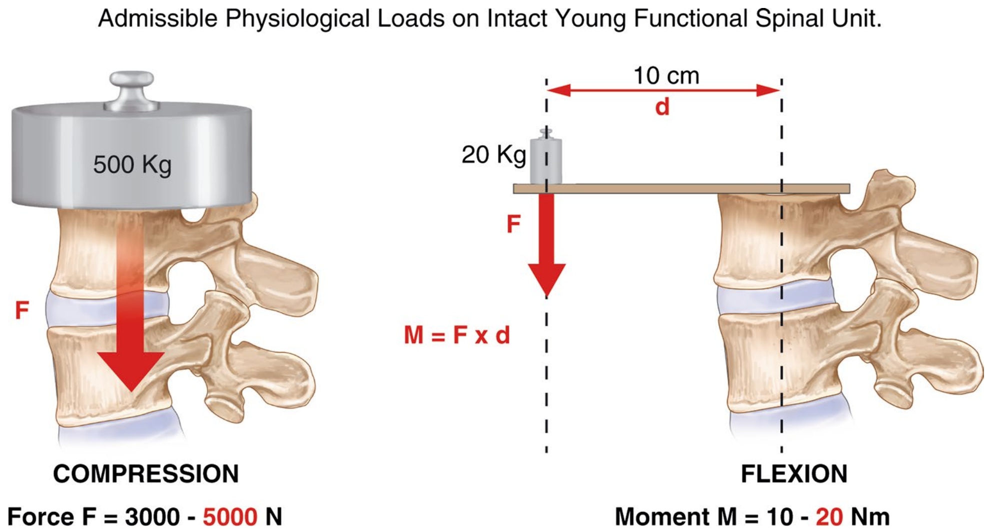


Fig. 1 Admissible physiological load on intact young functional spine. As shown by Nachemson et al., the maximal compression load supported by a spinal functional unit is 500 kg, but it decreases to 20 kg if a 10 cm lever arm is applied

The DE and the TS are directly related to the bending moment (BM), which is the product of the weight force (constant) and the arm length (variable) (Fig. 1). The arm length is the horizontal distance between the weight and the gravitational axis, and depends on the degree of kyphosis (greater kyphosis = greater lever arm).

In patients without sagittal imbalance, minor muscular efforts are sufficient to maintain the upright position (head and trunk weigh 35 kg in average, at 1 cm lever arm = 3.5 Nm as shown in example of Fig. 2): the balance is ''ergonomic''. In case of increased kyphosis (Fig. 2), with a 10-cm lever arm distance increase from the gravity line (GL), the bending moment becomes theoretically high enough to damage the vertebra (35 Nm). VCF can occur in this configuration and with a higher risk if the subject is osteoporotic.

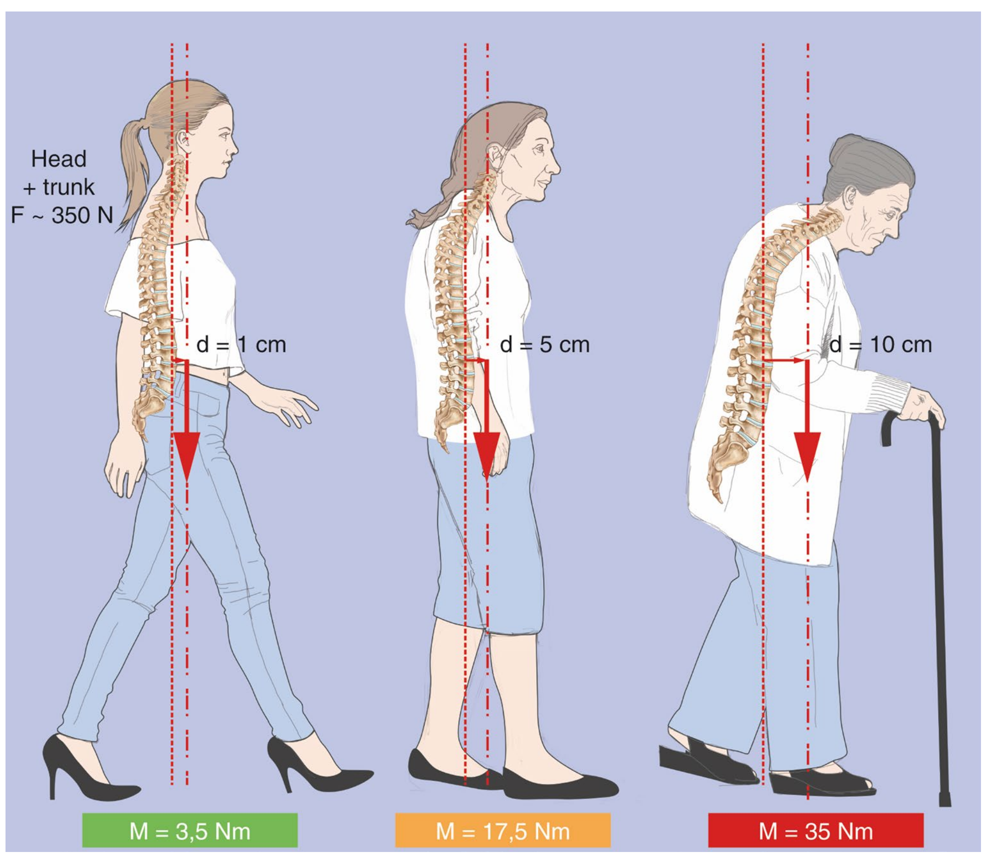


Fig. 2 Thoraco-lumbar bending moment increases with aging. With aging, disc degeneration induces loss of lumbar lordosis and increase of thoracic kyphosis, resulting in a forward shift of the center of gravity and a consequent increase of bending moments. Under adequate conditions (loss of muscular function and osteoporosis for example), bending moments can reach critical values and create vertebral fractures

In the static standing position, the weight of the overlying body segment, the compression and shear forces acting on the intervertebral discs are counterbalanced by the abdominal and paravertebral muscle efforts (posterior tension band, Fig. 3).

Paravertebral muscles are more solicited (up to 60%) in an imbalanced spine compared to the ergonomic spinal posture, to counterbalance the increased bending moment (Fig. 4). This muscular effort of counterbalancing induces an increase in compressive and shear forces by 20% on the lumbar discs due to small lever arms. When this becomes permanent, muscle fatigue sets in, leading to a reduction of the muscular compensatory capacity and potential additional degradation of the spinal functional unit.

Mechanically, decreasing the excessive thoracic kyphosis is surely a key factor in creating backward bending moments, resulting in reduced local stresses. As an example (Fig. 5), if the trunk is rocked forward, tilting the thoracic spine by 15°, then the bending moment in the T11 vertebra is about 22 Nm, which is excessive and may lead to a fracture. Restoring vertebral height in the case of a VCF cannot alone eliminate the risk of DE. However, an angular re-balancing of 1° creates a biomechanically more favorable bending moment by about 1.5 Nm.

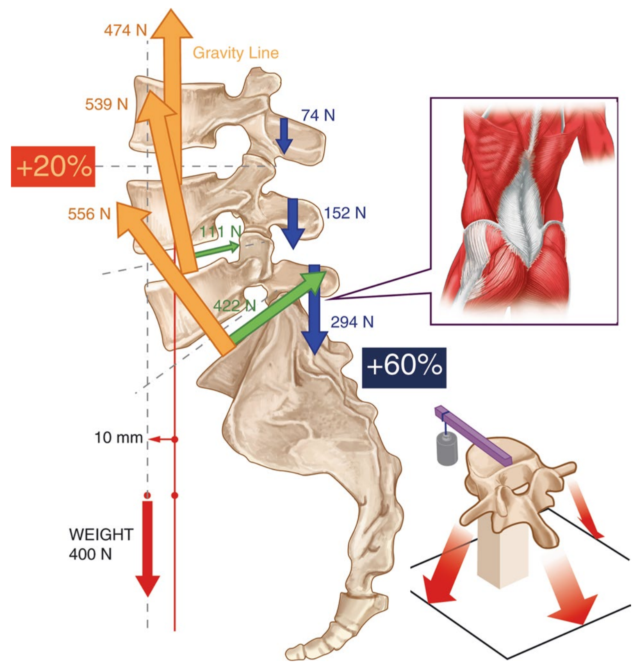


Fig. 4 Muscle work under abnormal balance conditions. Under abnormal conditions like sagittal imbalance due to disc degeneration or iatrogenic flatback, resultant bending moment increases and muscular work also has to increase. In this example, a 1 cm forward displacement of a 400 N weight induces a 60% increase of muscle work

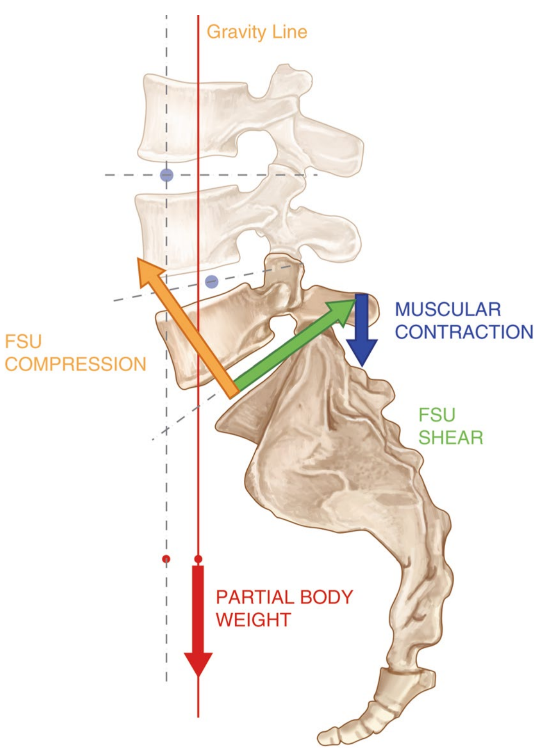
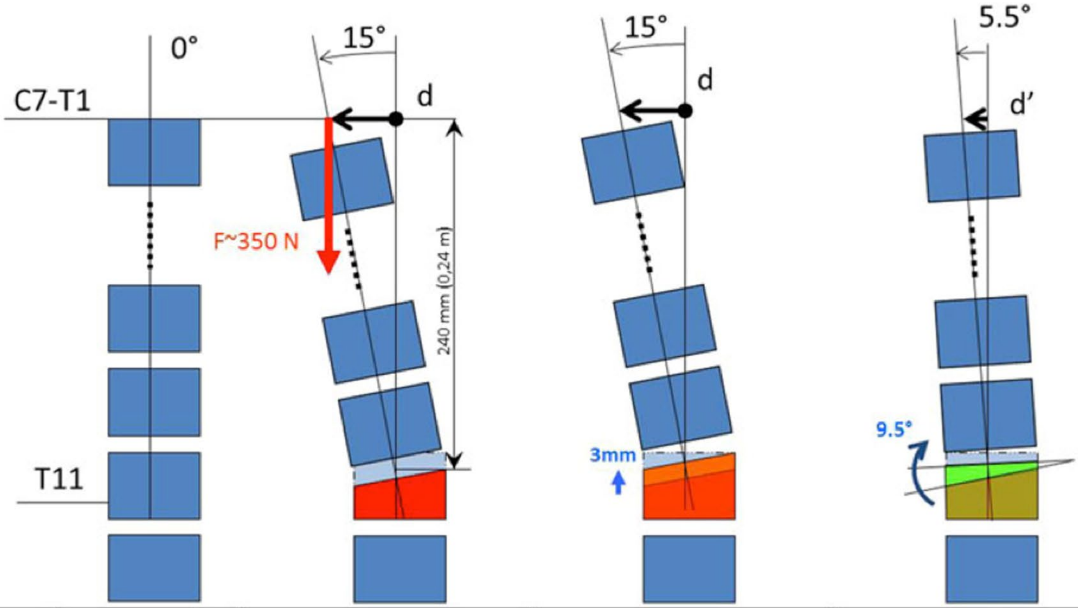


Fig. 3 Muscle work under ergonomic conditions. Under normal conditions, bending moments in the spine are counterbalanced by muscular action and vector force resultants equal zero

Thus, compared with the mean critical fracture threshold (20 Nm), 1 mm anterior height correction reduces by 13% the risk of subsequent vertebral compression fracture; 2 mm by 25%, etc. This biomechanical reasoning provides much information to understand the mechanisms of PJK/PJF above a fusion. The segment of the spine and body located on top of the UIV has a mass and a center of gravity that can be determined with a barycentremeter as described by Duval-Beaupere et al. [33]. Therefore, it is possible to evaluate the moment of forces applied on the first vertebra above the UIV knowing its distance from the center of gravity of the body part above it (Fig. 6).

Cervical inclination angle (CIA): a new sagittal parameter of economical balance assessment in the asymptomatic population

In static position, there is a balance between the weight of the overlying body segment, the compression and shear loads on the intervertebral discs, and the muscle counterbalancing efforts (tension of the spinal muscles and posterior ligaments). We analyzed the full spine EOS X-rays of an asymptomatic population in the upright standardized posture to find an anatomical parameter that could help to predict overstress at each segment of the thoraco-lumbar area.



	Normal	Kyphotic deformity	Height restoration	Angular restoration
Bending moment in T11	0 Nm	~ 22 Nm 350 x 0.24 x tan(15°)	~ 22 Nm	~ 8 Nm (-14Nm) 350 x 0.24 x tan(5,5°)
Angular deformation	0°	15°	15°	5.5°
Gain	-	-	0 Nm / mm	1.5 Nm / degree

Fig. 5 Effect of angular correction on bending moments. In this example, a 15° post-traumatic kyphotic deformity is simulated at T11. The bending moment is about 22 Nm. Restoration of height only, does not change the bending moment, where as correcting the kyphotic deformity by 9.5° results in a 14Nm bending moment decrease (1.5 Nm per degree of correction)

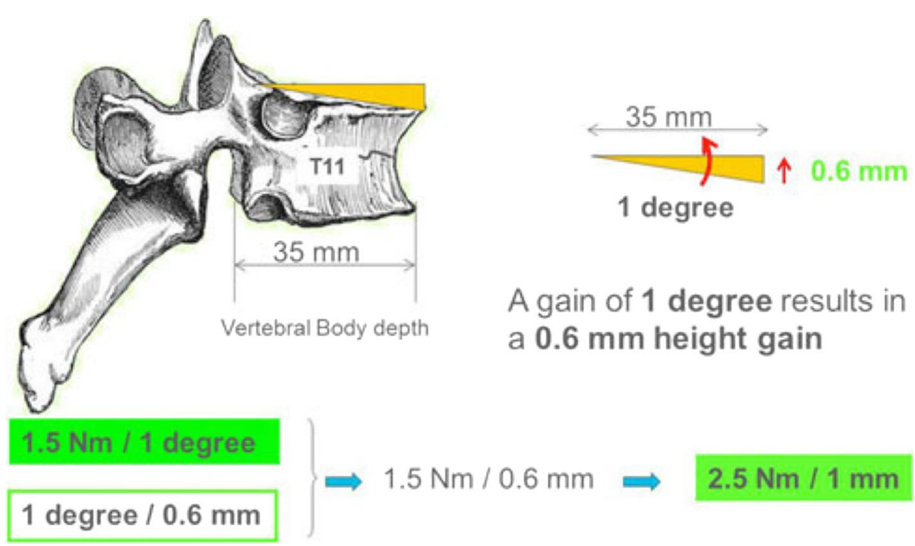


Fig. 6 Estimation of bending moments based on vertebral size. Knowing the antero-posterior (AP) diameter of a vertebra, it is possible to estimate the anterior wall height restoration necessary to produce a 1° kyphosis correction, which in turn represents a 1.5 Nm bending moment reduction

The position of the center of gravity of the head was studied in several papers and has been located just behind the sella turcica, close to Center of the Acoustic Meati (CAM) and on top of the dens of C2 [34]. The sella turcica is a very easily identifiable anatomical landmark on lateral full spine standing X-rays and located on the midline in the coronal view. Knowing that the odontoid-hip axis angle (ODHA) reliably reflects a globally balanced spine [32, 35], we decided to measure an anatomical angle at each level of the thoracic spine vertebra from T1 to T12, using a 3D reconstruction of the spine with EOS technology. This angle is the cervical inclination angle or CIA, and is described below.

Materials and methods

The EOS data of 137 asymptomatic voluntary subjects were extracted from a prospective database, after ethics committee approval (ID-RCB 2010-A01248-31). All X-rays were obtained in the standardized standing position as defined by Faro [36, 37]. The usual sagittal parameters such as pelvic parameters, lumbar lordosis, thoracic kyphosis, and cervical angles were measured. Those results have already been reported in a previous article [38].

The CIA was measured and is described as follows: for each thoracic vertebra from T1 to T12, we measured the angle between the mid-point of the sella turcica (ST), the mid-point of the thoracic vertebra and the horizontal line to each thoracic vertebral endplate mid-point (Fig. 7). The distance between the vertical line from the ST and the center of the endplate of each thoracic vertebra was also measured, as well as the vertical distance. The vertical and horizontal distances allowed us to spatially localize each vertebra. Two orthopaedic fellows did all the measurements twice independently. We also used values of the C7 slope, previously described, to calculate correlations [39].

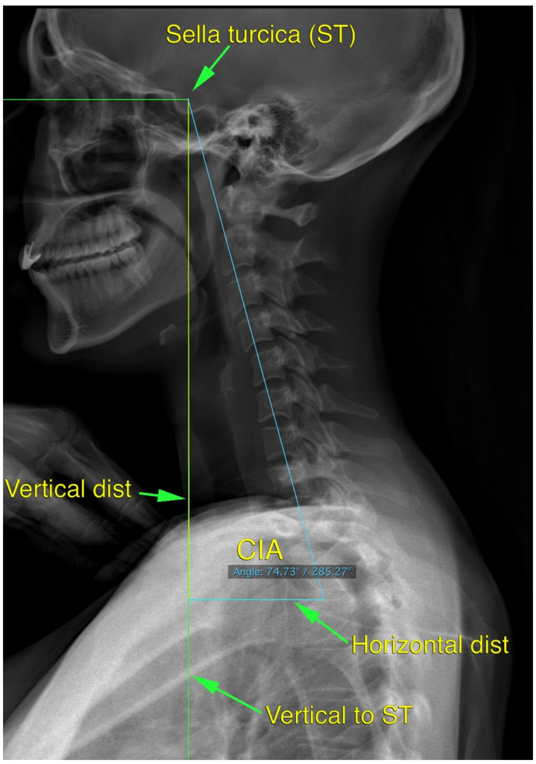


Fig. 7 Study measurements. CIA: angle between a line joining the center of ST to the center of the superior endplate of each thoracic vertebra, and a line drawn horizontally from the endplate center. For each level, the vertical distance was measured between the center of ST and the crossing point with the horizontal line drawn from the center of the superior endplate. Similarly, the horizontal distance was measured from the endplate center to the crossing point with the vertical ST line

Statistical analysis

Average values and standard deviations of CIA were calculated for each vertebral level from T1 to T12.

Correlations were calculated for T1–T5 alignment and T1–T5 segment inclination versus C7 slope, using linear regression and Pearson coefficient.

Results

The CIA average values for each thoracic vertebra of the 137 study subjects are reported in Table 1. The CIA average value progressively increases from T1 to T12, ranging from 74.83° for the lowest value to 83.82° for the highest. However, it appeared that the average values of the T1–T5 segment varied very little, between 74.9° and 76.85°, compared to the rest of the thoracic spine where there was a constant increase (Table 1 and Fig. 8).

Further analysis of the vertical and horizontal distances of each thoracic vertebra in reference to the ST vertical line showed that the vertebrae from T1 to T5 were in a straight line within the thoracic spine, as shown in Fig. 9.

Figure 10 describes the correlation between the C7 slope and the vertical inclination of the T1–T5 segment ($R^2 = 0.6383$).

Table 1 CIA average values per vertebral level (T1–T12)

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
Average (°) ($n = 137$)	76.85	76.00	75.21	74.83	74.9	75.38	76.24	77.42	78.82	80.35	82.02	83.82
Standard deviation (°)	5.3	5.1	5.02	5.02	4.92	4.86	4.79	4.65	4.49	4.33	4.15	3.99

Each average value, based on 137 subjects, is presented per level with standard deviation. It was noticed that the average value varies very little between T1 and T5, and then it increases progressively from T6 to T12

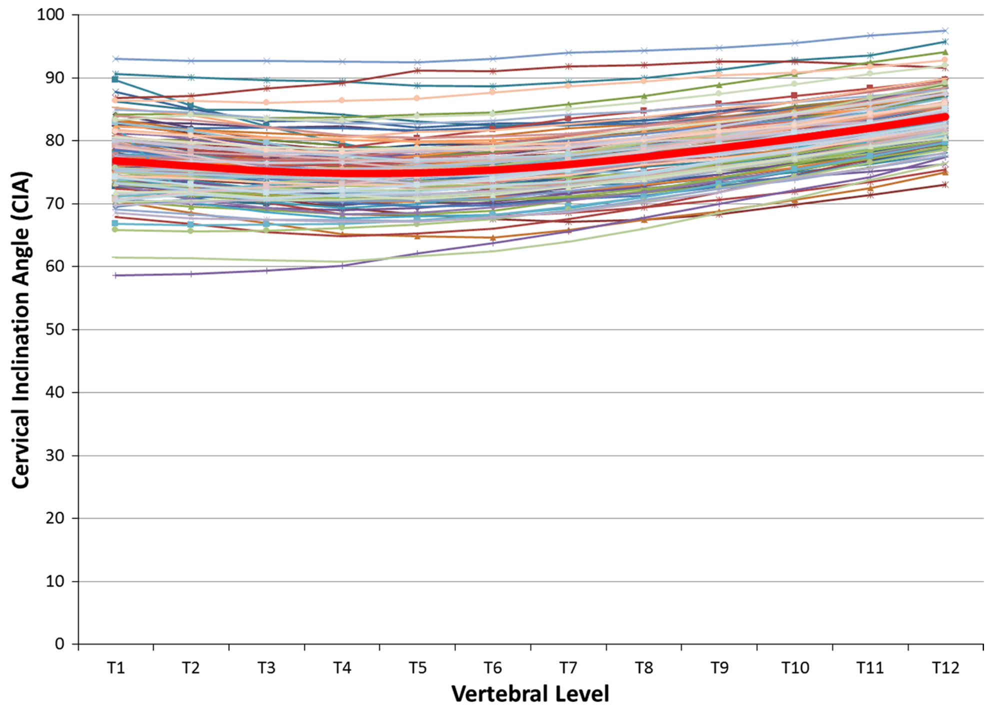


Fig. 8 CIA average value versus vertebral level (T1–T12). This graph shows the values for each of the 137 subjects. The line in red represents the average values calculated from the 137 subjects. It clearly stands out that the T1–T5 segment has an average CIA value that varies very little, as shown also in Table 1. It was thus hypothesized that T1–T5 vertebrae follow a straight line in all the subjects (see Fig. 9)

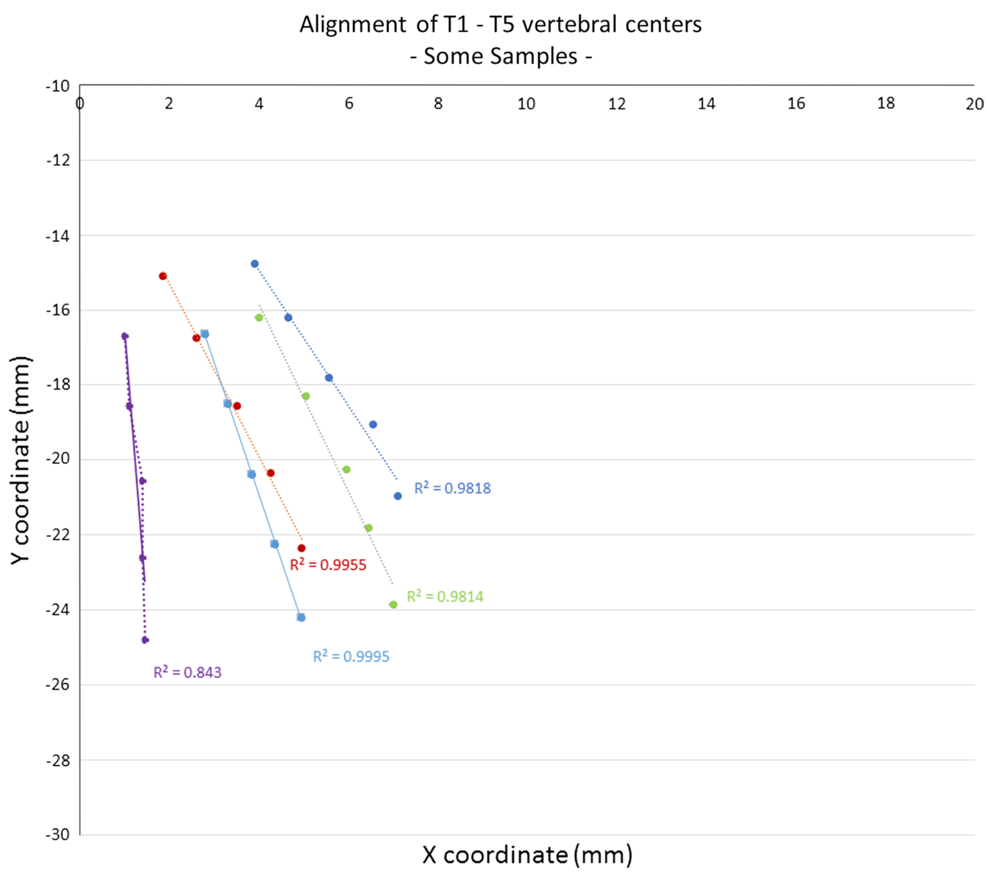


Fig. 9 T1–T5 alignment in a sample of study subjects. Using the vertical and horizontal distance measurements for each vertebra from T1 to T5, it was possible to localize them in reference to the ST vertical line. This graph clearly shows that T1–T5 vertebrae follow a straight line, with an average correlation coefficient, above 0.8 in the worst case (Pearson $R^2 > 0.8$)

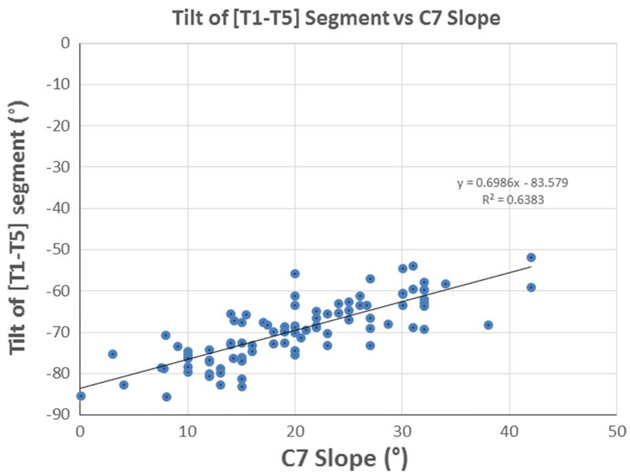


Fig. 10 Correlation of T1–T5 segment inclination versus C7 slope. The vertical inclination of the T1–T5 segment appeared to be correlated with the C7 slope for all the 137 subjects (Pearson $R^2 = 0.6383$). This means that any change in the vertical inclination of the T1–T5 segment will likely result in a modification of the C7 slope, which in turn will modify the cervical curve

Discussion

Sagittal vertical axis (SVA) is commonly used and considered as an important predictive factor for junctional construct failure [20, 21]. However, it does not take into consideration capital parameters, which are the head and neck and their weight. SVA is an adequate parameter to compare a patient balance over time but is not adequate to analyze the balance between patients. In some circumstances, the shoulders and upper limbs might also play a role. The CIA reflects the necessary harmony of the spinal curves and its importance for a balanced upright posture, as already supported by the concept of the conus of economy of Jean Dubousset [40].

The terms PJK (less deformity, non or less symptomatic) and PJF (more deformity, more symptomatic) do not reflect the biomechanical understanding we expose above. The main mechanism in both conditions is an excessive biomechanical stress as exposed at the beginning of this article (bending moment). However, the magnitude of the stress can be more or less important, which explains why some patients develop acute forms of junctional breakdowns (JBD) like fractures (thus a PJF) or a more progressive disease like adjacent segment degeneration (thus a PJK). This theory is further developed in part II of this article.

The analysis of the CIA shows that the T1–T5 segment is particular in the thoracic spine. The average value varies very little, between 74.9° and 76.85°, depending on the vertebral level (Table 1 and Fig. 8). In addition, Figs. 9 and 10 show us that T1–T5 vertebrae are very well aligned, and that there is a correlation between the T1–T5 segment inclination and the C7 slope ($R^2 = 0.6383$): if C7 slope increases, the T1–T5 segment is more horizontal and vice versa. This means that the T1–T5 segment can be considered as the base on which the cervical spine lies, just like the pelvis is the base of the lumbar spine. The T1–T5 segment defines the C7 slope, which in turn defines the cervical curve as shown in a previous publication [39]. This information is of paramount importance for the comprehension of junctional failures in the proximal and mid-thoracic spine.

Conclusion

This study shows that the T1–T5 segment can be considered as the base of the cervical spine. Its inclination defines the C7 slope and thus the type of cervical spine curve. The adequacy of the global balance in young and elderly asymptomatic populations can be determined with the ODHA [32]. Combining those two angles could allow us predict the risk of JBD in a population of patients with long lumbo-sacral fusions. A detailed analysis of 12 patients with thoracolumbar JBD is presented in part II of this article.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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