ENGINEERING CONCEPTS IN ANALYSING LUMBOSACRAL LOAD IN POST-OPERATIVE SCOLIOTIC PATIENTS

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Abstract

Lumbosacral alignment plays a major role in the mechanical low back pain in normal population. Malalignment causes increased strain to the muscles and ligaments around it which eventually leads to mechanical low back pain and discomfort. The level of strain a ligament receives in the lumbosacral junction depends upon the lumbosacral angle and the load exerted on it. If there is an easy way to find the load exerted at the lumbosacral junction, then it would be trouble free for the physicians to examine. Hence, the treatment can be planned accordingly. This study analysis the angle, net force produced and stress faced by the ligaments around the lumbosacral joint in postoperative scoliosis patients using radiographic images. Study design was analytical, observational cross sectional study. Radiographs of 30 patients were collected and one sample 't' test was used for data analysis with 'p' value set as 0.05 as level of significance .The mean lumbosacral angle of the postoperative scoliotic patients was found to be 45.56 degrees and the standard deviation was ± 8.7156. The results suggest that patients who underwent scoliosis correction surgery did not have an optimal lumbosacral angle of 30 degrees.

Keywords: Force magnitude, Center of Pressure, Center of Mass, Lumbosacral stress.

1. Introduction

Human vertebral column consists of 24 articulating and 9 fused vertebrae (7 cervical, 12 thoracic, 5 lumbar, 5 fused sacral and 4 fused coccyx vertebrae), which totals to 33 vertebrae. Each articulating vertebra is separated by an intervertebral disc and helps in formation of curves and load bearing. Vertebral column and lower limbs are connected or linked via pelvis. Pelvis consists of sacrum, coccyx, ischium,

Nomenclatures

a	Acceleration
F	Force
F_g	Force Gravity
g	Gravity
$\overrightarrow{F_g}$	Gravitational force
$\overrightarrow{F_g} \parallel$	Parallel force
$\overrightarrow{F_g} \perp$	Perpendicular force
L_5	Fifth lumbar vertebra
m	Mass
S_1	First sacral vertebra

Greek Symbols

Θ	Angle in a triangle

Abbreviations

AIS	Adolescent Idiopathic Scoliosis
CoM	Center of Mass
CoP	Center of Pressure
DICOM	Digital Imaging and Communications in Medicine
LS	Lumbosacral
NIOSH	National Institute for Occupational Safety and Health

pubis, acetabulum, sacroiliac joint and pubic symphysis. Base of sacrum acts as the articulating surface with fifth lumbar vertebra, sacroiliac is the joint formed by sacrum and ilium. While acetabulum acts as the articulating surface with femur bones. Weight from the head, arm and trunk are passed through vertebral column and transferred to the lower limbs through sacrum and sacroiliac joint. National Institute for Occupational Safety and Health (NIOSH) guidelines for manual (1994) lifting concluded that the joint between fifth lumbar vertebra (L_5) and first sacral vertebra (S_1) is the joint of greatest lumbar stress during lifting. Study done by C. W. Spoor et al. found that 20% reduction in vertical sacroiliac joint shear resulted in 70% increase of sacroiliac joint compression force [1].

1.1. Lumbosacral junction

Lumbosacral joint faces a great anterior shear imposed by the body weight. This joint is stabilized by strong iliolumbar and sacrolumbar ligaments along with the L_5 - S_1 facet joints, which prevents excessive anterior shear of L_5 on S_1 [2]. Lumbosacral junction forms an angle called Lumbosacral angle. It plays a major role in weight distribution. Any increase or decrease in lumbosacral angle leads to an imbalanced weight distribution, altered posture and sacroiliac joint dysfunction. The most common way of measuring lumbosacral angle was first proposed by Ferguson [3]. He measured the angle formed between base of sacrum with the horizontal plane known as Lumbosacral angle (Fig. 1). The optimal lumbosacral angle is approximately 30 degrees [4]. As mentioned above, optimal

30 degree of lumbosacral angle transfers the weight it receives to pelvis and lower limbs equally without any stress. If the lumbosacral angle is altered, then it leads to increased lordosis in lumbar region or flat back and increased stress in ligaments around the joint.
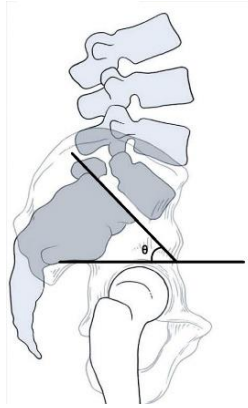

Fig. 1. Lumbosacral (LS) angle.

In normal persons, vertebral column is arranged linear in frontal, transverse plane and angular in sagittal plane. Although, in scoliosis patients, vertebral column is arranged angular in all the three planes. The vertebrae are tilted in frontal and twisted in transverse plane. Vertebral tilt can be found by Cobb angle measurement in frontal plane. Although, twisted or rotated vertebrae can be found by Nash-Moe or Perdriolle methods. Scoliosis mostly occurs in thoracic, thoracolumbar and lumbar regions. According to Maurice Abitbol, development of lumbosacral angle is not related to age, weight or height. Rather, it is related to progressive achievement of the erect posture [5]. Hence, individuals with spinal or postural deformities like scoliosis are more commonly involved with altered lumbosacral angle.

When scoliosis patients undergo corrective surgery, surgeons focus only on correcting the scoliosis curve (vertebrae causing scoliosis curve). While correcting scoliosis, along with scoliosis curve, proper attention must be given to the lumbosacral angle too. This is because, most of the patients who underwent scoliosis corrective surgery complained of low back pain soon or later. Altered lumbosacral angle is the main root cause for the mechanical low back pain. When scoliosis patients undergo corrective surgery, surgeons implant Harrington rod made up of stainless steel or titanium along the course of the expected normal vertebral curve and screw the vertebrae to it using pedicle screws. Thus, rearrange the vertebral column to a new or normal position. The new vertebral pattern sits over the sacrum with a new lumbosacral angle, which might be in optimal or in varying degree.

1.2. Lumbosacral and center of mass

Earlier, several studies have provided enough evidence that there is a strong relation between lumbosacral angle and Center of Mass. Pasha et al. [6] conducted a study on biomechanical effects of spinal fusion on the sacral loading in adolescent idiopathic scoliosis with 9 subjects. They found that stress distribution on the

sacrum, Center of Mass (CoM) and Center of Pressure (CoP) were significantly different between pre and post-operative. The position of CoP in S_1 with respect to CHVA (Global Coordinate System) and the biomechanical loading on sacrum varied between pre and post-operative subjects. The distance between projection of CoM of Trunk and CoP of S_1 on transverse plane was decreased in both mediolateral and anteroposterior directions after surgery. A significant relationship was observed between sacral slope and the position of CoP of S_1 and CoM of Trunk. As the sacral slope increases, the anteroposterior distance between CoM of Trunk and CoP of S_1 decreased significantly in postoperative subjects. But this study did not convey whether the level of fusion or number of vertebrae fused lead to the variance in CoM and CoP.

Carvalho de Abreu et al. [7] have done a study on influence of surgical treatment of adolescent idiopathic scoliosis on postural control. They found that the patient's height after spinal realignment was increased and accompanied with a larger CoP oscillation when compared with the age matched controls. But they were not sure whether the sensorimotor impairment / sensory integration problem causes this or biomechanical factors in the Adolescent Idiopathic Scoliosis (AIS). Also, another study done by Nohara et al. [8] on lumbar disc degeneration in patients with adolescent idiopathic scoliosis with spinal fusion claims that 48% of disc degeneration occurs at L_5 Lumbosacral (LS) and segments adjacent to fused vertebrae has only 8% of chance. They have also mentioned that there is no data on lower unfused segments angular magnitude and occurrence of disc degeneration because of lower instrumented vertebrae. As such, there is no any single consensus available on whether increasing the fusion area for greater scoliosis correction or limiting the lumbar fusion area while leaving some uncorrected angle leads to a better outcome.

These studies give rise to the questions regarding the CoM, CoP oscillation, optimal lumbosacral angle and the net force acting on L_5 vertebra in the post-operated scoliosis patients. This led us to investigate the lumbosacral angle post operatively. The objective of this study is to analyse the lumbosacral angle in post-operative scoliosis patients.

2. Methods

The sampling method followed was a non-probability convenient sampling. The study design was observational cross sectional study.

2.1. Data collection and evaluation of lumbosacral angle

Data collection was done at Government General Hospital, Chennai, India. Proper consent was obtained from the radiology department before collecting data. Radiographs were taken with patients in the lying position. As during standing, the patient might tilt their pelvis unknowingly. Radiographs of the 30 patients between the age group 10 to 25 years who underwent scoliosis correction surgery were obtained. Baseline assessment like age, sex and date of surgery done were also noted. A sample of 3 patient's data are provided below (refer Table 1). The lumbosacral angle was measured in radiographs using the angle formed between base of sacrum with the horizontal plane (Fig. 2). Angle was measured digitally by Sante DICOM viewer, version 5.0.4. The percentage difference while measuring the angle was found to be less than 1.6%.

Table 1. Patient details.

Gender	Age	Date of Surgery	Lumbosacral Angle
F	14	10-02-2015	58.45
M	15	20-05-2014	51.8
M	17	31-10-2011	43.98

2.2. Evaluation of force acting on vertebra

Let us consider a rectangle placed over triangle as a lumbar vertebra over sacrum, with θ as lumbosacral angle. (Fig. 3) Now, XZY is a right angled triangle with θ at Y. Let C be the center of mass of L_5 vertebra, XY be the base of sacrum, $\overrightarrow{F_g}$ is the gravitational force or body weight acting, $\overrightarrow{F_g \parallel}$ is the parallel force or anterior shear acting on vertebra parallel to XY slope, $\overrightarrow{F_g \perp}$ is the perpendicular force acting perpendicular to XY slope, A and B are the two points where gravitational and perpendicular force intersects XY.

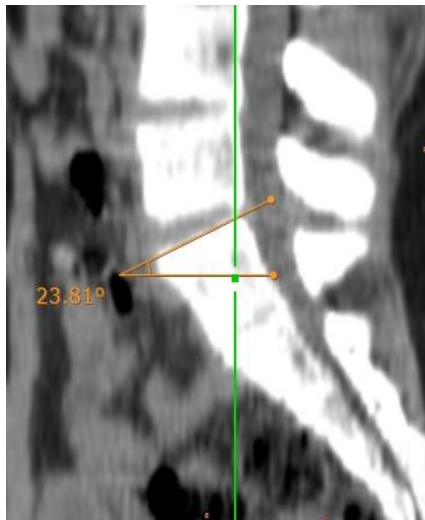$$\angle XZY = 90° \tag{1}$$

$$\angle XYZ = \tan \theta \tag{2}$$
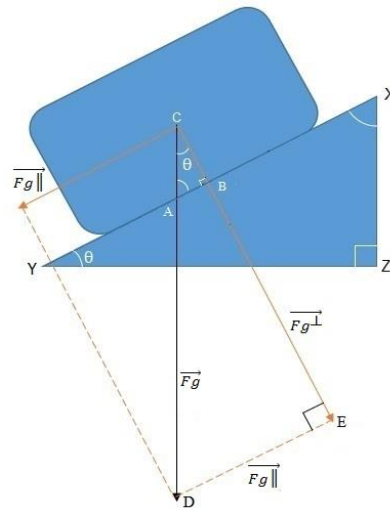

Fig. 2. LS angle marking in radiograph.

Fig. 3. Geometry of LS junction.

Applying Trigonometric rules to find the angle in a given triangle, we get:

$$\tan \theta = \frac{Opposite}{Adjacent}$$

It is understood that, opposite to θ is $\overline{XZ}$ line and adjacent to θ is $\overline{YZ}$ line. So, $\tan \theta$ is $\overline{XZ}$ divided by $\overline{YZ}$.

$$\tan \theta = \frac{\overline{XZ}}{\overline{YZ}}$$

From the above equation, θ is derived as:

$$\theta = \tan^{-1} \frac{\overline{XZ}}{\overline{YZ}} \qquad (3)$$

After finding the lumbosacral angle, using it, the net force exerted on the lumbosacral joint will be found. Any force directed at an angle is resolved into horizontal and vertical components. One directed parallel to the slope and another perpendicular to it.

Parallel component + Perpendicular component = Total force due to Gravity.

$$\overrightarrow{F_g \parallel} + \overrightarrow{F_g \perp} = \overrightarrow{F_g}$$

Using Eq. (3), θ at Y can be found. Since all the angles inside a triangle sums to 180°;

$$\angle XYZ + \angle XZY + \angle YXZ = 180°$$

Using Eqs. (1) and (3), we can say that:

$$\theta + 90° + (90° - \theta) = 180° \qquad (4)$$

So, in ΔXYZ, $\angle XZY = 90°$, $\angle XYZ = \theta$, $\angle YXZ = 90° - \theta$. The force vectors from the center C of L$_5$ vertebra, F_g and $F_g\perp$ passes through the slope $\overline{XY}$ at A and B. This forms another right angled triangle CBA. From geometrical rules (Alternate Interior Angles Theorem), we know that if two parallel lines are cut by a transversal line, then alternate interior angles are congruent. Applying it here, F_g is parallel to $\overline{XZ}$ and $\overline{XY}$ acts as a transversal line. Hence:

$$\angle YXZ = \angle CAB$$

As mentioned earlier, since any force directed at an angle is resolved into parallel to the slope and another perpendicular to the slope, $F_g\perp$ is perpendicular to $\overline{XY}$, forming 90°. So, in ΔCBA, $\angle CBA = 90°$, $\angle CAB = 90° - \theta$, $\angle BCA = U$ (Unknown). As all the angles inside a triangle sums to 180°, we get:

$$\angle BCA + \angle CBA + \angle CAB = 180°$$

$$U + 90° + (90° - \theta) = 0°$$

$$U = \theta \qquad (5)$$

Applying Eq. (3) in (5), we get:

$$\angle XYZ = \angle BC$$

Shifting the parallel force component downward, since it is parallel to the slope $\overline{XY}$, it forms another right angled triangle CED, where its opposite side $\overline{DE}$ is formed by $F_g\parallel$, adjacent side $\overline{CE}$ is formed by $F_g\perp$, and hypotenuse side $\overline{CD}$ by F_g. Using trigonometry, the magnitude of parallel and perpendicular force due to gravity can be found. To find the magnitude of parallel component:

$$\frac{\overline{F_g\parallel}}{F_g} = \sin\theta$$

$$\overrightarrow{F_g \parallel} = \overrightarrow{F_g} \sin\theta \qquad (6)$$

To find the magnitude of perpendicular component:

$$\frac{\overrightarrow{F_g \perp}}{\overrightarrow{F_g}} = \cos \theta$$

$$\overrightarrow{F_g \perp} = \overrightarrow{F_g} \cos \theta \tag{7}$$

Since Force equals to Mass timed Acceleration ($F = ma$) the gravitational force can be resolved into mass and acceleration. Here acceleration is gravity, hence:

$$\overrightarrow{Fg} = \text{m g} \tag{8}$$

Applying Eq. (8) in (6) and (7), we get:

$$\overrightarrow{F_g \parallel} = m\,g\,\sin \theta \tag{9}$$

$$\overrightarrow{F_g \perp} = m\,g\,\cos \theta \tag{10}$$

As all the vertebrae are separated by the intervertebral discs, there is no friction produced in the lumbosacral joint. Thus, the co-efficient of friction is not calculated here. In absence of friction, the acceleration of an object over an inclined plane is the value of parallel component ($\overrightarrow{F_g \parallel}$) divided by mass (m), which gives the equation:

$$a = g \sin \theta \tag{11}$$

The forces acting on vertebra are, anterior or parallel force ($\overrightarrow{F_g \parallel}$), downward or perpendicular force ($\overrightarrow{F_g \perp}$) and upward force (opposite of $\overrightarrow{F_g \perp}$) exerted on vertebra by the slope $\overline{XY}$. Net force is the vector sum of all the forces acting on the vertebra. Hence, the net force would be:

$$\overrightarrow{F_g \parallel} + \overrightarrow{F_g \perp} - \overrightarrow{F_g \perp} = \overrightarrow{F_g \parallel} \tag{12}$$

3. Results and Discussion

Out of the 30 samples, 12 were males and 18 were females (Fig. 4). Since the standard normal lumbosacral angle across the population was known, comparison was made using one sample 't' test, with 'p' value set as 0.05 as level of significance. The mean lumbosacral angle of the postoperative scoliotic patients was 45.56 degrees and the standard deviation was ± 8.7156. The one tail critical value was 1.7108, whereas, test statistic value was 8.9278 and p value was less than 0.05. Since the test statistic value of 8.9278 is greater than the critical value of 1.7108 and p value is lesser than 0.05, as a result, we reject null hypothesis. The mean postoperative scoliotic lumbosacral angle is greater than 30 degrees.

We also calculated the net force acting on the L_5 vertebra and the forward acceleration of it over the base of sacrum. According to Aydin Tozeren weight of head, neck, trunk and upper limb weighs 63.06% of total body weight [9]. Let us assume adults with optimal lumbosacral angle (30°) and 65 Kgs of weight. Therefore, the load of head, trunk and upper limb will be 40 Kgs. (63.06*65/100=40.9) Using Eq. (9), it is found that a net force of 196 N acts on the L_5 vertebra and ligaments and muscles around the lumbosacral joint prevents the forward or anterior sliding of L_5 vertebra at the rate of 4.9 m/s^2. On the other hand, for postoperative scoliotic patients with the lumbosacral angle of 45.5° (mean), it is found that a net force of 279.49 N acts on the L_5 vertebra and

preventing acceleration of 6.98 m/s^2. For a normal adult of 45 years, with 70 Kgs weight and 1.68 m height, the intervertebral disc pressure at $L_4 - L_5$ during supine lying was found to be 0.10 MPa and 0.50 MPa during relaxed standing [10]. Also, the intervertebral disc at L_3 receives a compressive load of 300 N during supine lying and 700 N during normal standing [11]. Our results showed that there is a significant difference in the lumbosacral angle between the normal (30°) and postoperative scoliotic patients (45.5°).
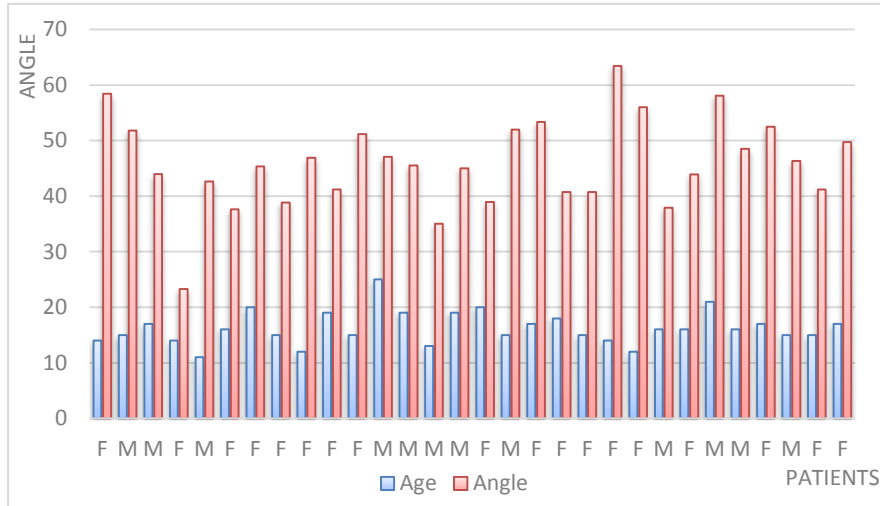
Fig. 4. LS angle in post-operative patients.

The Lumbosacral angle is compared with 19 patients (9 males, 10 females) suffering from scoliosis who did not take any treatment (non-operative) to correct scoliosis. They were in the age group between 45 to 65 years old. The mean lumbosacral angle of the non-operative scoliotic patients was 40.9 degrees and the standard deviation was ± 7.5548. Using Eq. (9), the net force acting on L_5 vertebra was found to be 256.64 N. We do not find any relation between age or gender on lumbosacral angle. Even though, females are more commonly affected by scoliosis, age and gender do not have any significant impact on the postoperative lumbosacral angle. Lumbosacral angle does not increase with the age or with gender (Fig. 5). A long term study on the postoperative scoliotic patients may suggest any. Since the sacrum is attached with ilium, increased and decreased lumbosacral angle in long term might lead to nutation and counternutation. Nutation refers to sacral flexion, when base of the sacrum moves anterior and inferior, coccyx moves posterior and superior. This in turn leads to increased pelvic outlet. While counternutation refers to sacral extension, when base of the sacrum moves posterior and superior, coccyx moves anterior and inferior. This in turn leads to increased pelvic inlet. However, the amount of movement occurring during nutation and counternutation are very minimal.

The variation of 15.5° can be a major reason for the low back ache, spondylolisthesis, lumbosacral instability, sacroiliac joint dysfunction, nerve roots compression and lower cross syndrome as it increases the magnitude of the forces acting at the lumbosacral joint. The net force acting on L5 vertebra is

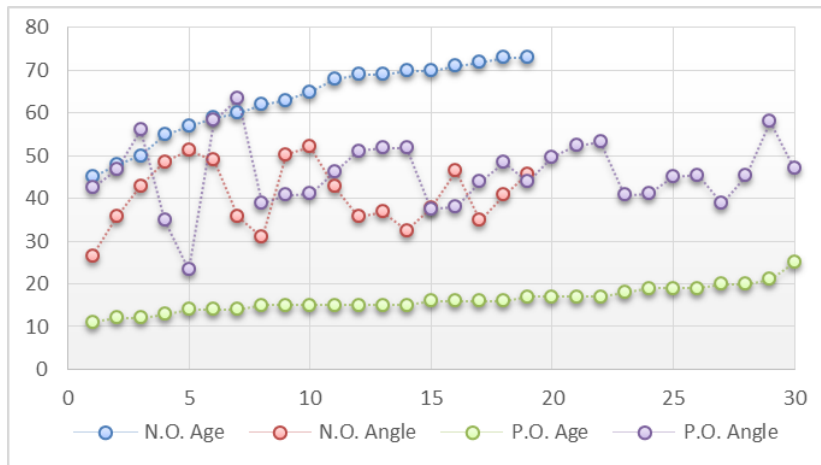increased along with the increase in Lumbosacral angle, Fig. 6. Both are proportional to each other.

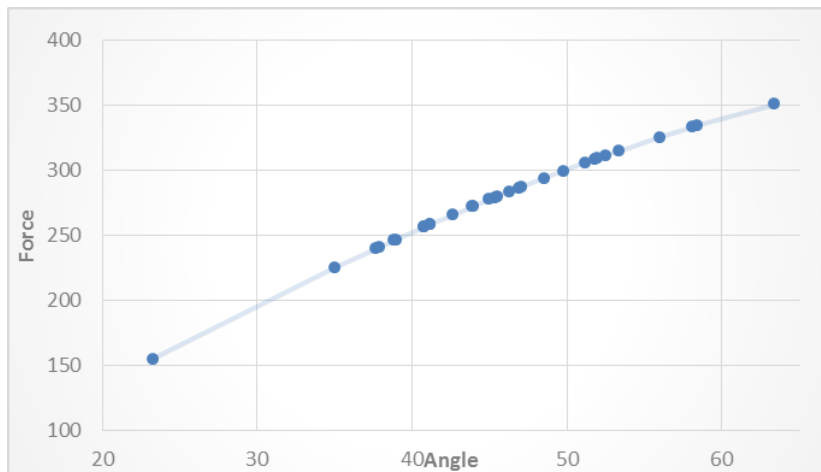**Fig. 5. Age and angle between non-operative and post-operative.**

Fig. 6. Effect of LS angle on force.

The net force of 279.49 N acting on the L_5 vertebra makes the iliolumbar and sacrolumbar ligaments to bear more stress. The L_5 - S_1 facet joints, receives excessive anterior shear of L_5 on S_1, which might make it more prone to initial area of lumbar body and disc degeneration (Fig. 7). These results can only be verified by creating the 3D model of spine, after processing the CT scan files [12] [13] and doing finite element analysis [14, 15]. The results from this study and results from finite element analysis can be compared for better perfection. As mentioned earlier, scoliotic patients have an altered CoM and CoP. Since not enough care was given to the lumbosacral angle when compared with scoliosis curve in surgical planning, the resultant lumbosacral angle after scoliosis corrective surgery seems to be not

optimal. Thus, the CoM and CoP still falls away from the normal, making the adjacent muscles, ligaments and joints to bear more stress, which eventually sooner or later will lead to low back pain.
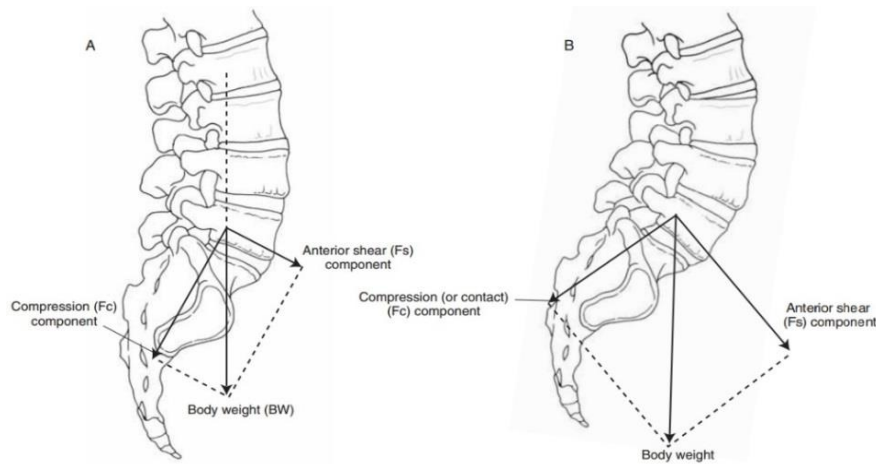

Fig. 7. Magnitude of forces at LS junction. A- Normal, B- Abnormal [11].

Large force always acts in the longitudinal direction along spine. Since sacroiliac joint is parallel to the longitudinal force, it is more vulnerable to shear because of its flat surface. In addition to strong ligament support, muscle forces are also required to raise friction which resists shearing [16]. A study done by Aycan et al. [17] on lumbosacral angle evaluation in patients with lumbar disc herniation concluded that during preoperative, postoperative treatments and follow ups, biomechanical parameters must be also considered and carefully evaluated. One of the major causes for failed back syndrome is postoperative lumbosacral instability. Study conducted by Naderi et al. [18] on postoperative lumbosacral instability also supports our findings. They concluded that facet resection, increased facet angle and decreased lumbar lordosis contribute the lumbosacral instability. A careful preoperative planning could reduce lumbosacral instability. Thus, while planning for a corrective surgery, surgeons must also give proper attention to the CoP and lumbosacral angle for a better biomechanical achievement.

4. Conclusion

This study portrays an easy method to evaluate the lumbosacral load for a given patient using their radiographs. This will be helpful for the clinicians to examine their patient's lumbosacral junction load and plan the treatment accordingly. This study revealed that CoP and lumbosacral angles in the postoperative scoliotic patients were not back to normal. Even though the surgeons reduced the Cobb angle which was visually noticeable, they must provide more attention to the other invisible components like CoM and CoP of the scoliotic patients. While using implants, it must be aligned geometrically providing the curves, increasing the functionality and preserving the CoM and CoP within the base of sacrum. Hence, a normal lumbosacral angle can be maintained.

Acknowledgement

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