The impact of intra-operative sternum vertical displacement on the sagittal curves of the spine

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Abstract Patient positioning is an important step in spinal surgeries. Many surgical frames allow for lumbar lordosis modulation due to lower limb displacement, however, they do not include a feature which can modulate thoracic kyphosis. A sternum vertical displacer (SVD) prototype has been developed which can increase a subject's thoracic kyphosis relative to the neutral prone position on a surgical frame. The kyphosis increase is obtained by lifting the subject's torso off the thoracic cushions with a dedicated sternum cushion that can be displaced vertically. The objective of this study was to evaluate the impact of SVD utilization on the sagittal curves of the spine. Experimental testing was performed on six healthy volunteers. Lateral radiographs were taken in the neutral and sternum raised positions and then analyzed in order to compare the values of sagittal curves. The displacement of volunteers and surgical frame components between positions was recorded using an optoelectronic device. Finally, interface pressures between the volunteers and surgical frame cushions were recorded using a force sensing array. Average results show that passing from the neutral to sternum raised positions caused an increase of 53% in thoracic kyphosis and 24% in lumbar lordosis; both statistically significant. Sensors showed that the sternum was raised a total of 8 cm and that interface pressures were

considerably higher in the raised position. The SVD provides a novel way of increasing a patient's thoracic kyphosis intra-operatively which can be used to improve access to posterior vertebral elements and improve sagittal balance. It is recommended that its use should be limited in time due to the increase in interface pressures observed.

Keywords Spine · Surgical positioning · Kyphosis · Surgical frame

Introduction

In recent years, positioning objectives for spinal surgeries have evolved to include intra-operative modulation of the patient's vertebral column geometry [1, 2]. Thus far, the primary focus has been on the modulation of lumbar lordosis due to positioning of the lower limbs [3–5] and as a consequence many surgical frames now allow flexion or extension of patients' hips. While some studies have attempted to quantify the impact of prone positioning on thoracic kyphosis [6–8], no devices have been introduced which allow modulation of thoracic kyphosis intra-operatively.

A new multi-functional positioning frame (MFPPF) has been developed. The MFPPF holds patients in the prone position with two thoracic cushions, two pelvic cushions, and a lower limb positioning feature. It also includes a sternum vertical displacer (SVD) feature, still in the prototype phase, which is a portable device that can be placed under the MFPPF, or other similarly designed surgical frames, and lifts the patient's torso up off of the thoracic cushions. Its Y-shaped cushion, made of memory foam material, is meant to interface with the patient anterior to the thoracic cushions just below the sterno-clavical joint and should not surpass the sternum distally to avoid

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pressure on the abdomen. Displacement, offset by 15° posteriorly relative to the vertical, is obtained with an electronically operated jack.

The objective of this study is to evaluate the impact of the SVD device on the sagittal curves of the spine for subjects on the MFPP. It is hypothesized that use of the SVD can significantly and safely increase thoracic kyphosis relative to the neutral prone position.

Methods

Experimental testing was performed on six asymptomatic young adult volunteers, three males and three females aged 20–28 (Table 1), at Sainte-Justine University Hospital Center in Montreal with approval obtained from the ethics committee. Subjects were weighed and their heights recorded. They were then placed in the prone position on the MFPP where two 36 in. (91.4 cm) lateral radiographs of their spines were acquired; one in the neutral position and one with the SVD lifted approximately 15 cm. Each radiograph was analyzed using Synapse image analysis software (Fujifilm Medical Systems USA) and the following indices were measured: T4–T12 thoracic kyphosis, apical thoracic segment (from T4 to T8) intervertebral disc angles and space (defined here as the distance between the posterior tips of vertebral body endplates interfacing a given disc), L1–L5 lumbar lordosis, T4–S1 sagittal plane decompensation (vertical distance between T4 and S1 vertebral body centroids), and ribcage width at the T5 level (anterior edge of ribcage to posterior edge of T5 perpendicular to horizontal reference). Scaling of radiographic measurements to account for the perspective projection of the radiographic image was done based on the thickness of an oblique radio-opaque beam of the surgical frame that was used as a calibration object. The change in kyphosis and lordosis between positions was statistically analyzed using a paired *t* test performed with STATISTICA V8 software (StatSoft Inc.).

Motion between radiographic positions of both the subjects and SVD was recorded using a 3D optoelectronic system (Polaris Northern Digital Inc.) with reflective markers placed on the SVD jack and subjects' head (posterior to the ear), lateral-posterior portion of the ribcage at the T5 level, and hip joint (Fig. 1).

Subject thoracic mobility was evaluated two different ways; actively and passively. In the first test, subjects were asked to laterally bend their torso to the left and right in the standing position while maintaining their feet shoulder width apart; as is done for pre-operative scoliosis patients. The maximum lateral displacement of T1 relative to S1 in each case was recorded using a plumb line, ruler and level. In the second test, subjects were placed in the lateral left and right decubitus positions with a 10 in. diameter cylindrical rigid support (fulcrum) placed under the mid portion of their ribcage. The angle made between points T1, the apical vertebra over support, and S1, all identified via palpitation, was measured with a goniometer.

Finally the interface pressure between the subjects and MFPP cushions in each radiographic position was recorded using a force sensing array (FSA—Vista Medical, Winnipeg) composed of 225 sensors with a capacity of up to 300 mmHg and analyzed by accompanying software (FSA4). The complete experimental setup can be seen in Fig. 1.

Results

A summary of spinal geometries in the neutral and sternum lifted positions, as well as the flexibility data, can be found in Table 1 and can be visualized with the radiographs of all cases in Fig. 2. Going from the neutral to sternum raised position caused a statistically significant ($P = 0.001$) increase in kyphosis which averaged 14° ($\pm 5^\circ$) or 53%. It also caused a statistically significant ($P = 0.002$) increase in lordosis averaging 10° ($\pm 4^\circ$) or 24%, an increase in decompensation averaging 81 mm (± 15 mm), and a ribcage compression ranging between 10 and 30 mm. The Pearson's

Table 1 Subject data and spinal geometries in the neutral and sternum lifted positions

#	Sex	Weight (kg)	Height (cm)	Average lateral bending (cm)	Average fulcrum bending (°)	Thoracic kyphosis		Lumbar lordosis		Decompensation (mm)	
						Neutral (°)	Raised (% change)	Neutral (°)	Raised (% change)	Neutral	Raised
1	F	47	155	17	13	21	33° (+57)	46	57° (+24)	19	97
2	M	65	176	38	34	25	36° (+44)	29	34° (+17)	18	113
3	M	52	169	25	11	32	48° (+50)	49	60° (+22)	50	104
4	F	54	161	21	23	34	41° (+21)	42	53° (+26)	38	120
5	F	68	158	22	11	44	61° (+39)	40	56° (+40)	57	135
6	M	86	185	35	18	19	40° (+111)	38	44° (+16)	35	131

Fig. 1 **a** Experimental setup with a patient in the raised position, **b** details (CAD model) of the SVD cushion

Fig. 2 Radiographs of subjects one to six in **a** neutral, **b** raised positions

correlation between the percentage change in kyphosis between positions and flexibility measurements was, respectively, 0.15 for lateral bending and 0.47 for fulcrum bending.

As can be observed on the radiographs, the apex of the increase in kyphosis is inline with the SVD line of action at about the T5 or T6 level. Within the apical thoracic segment the average intervertebral disc angle increased from

Table 2 Apical spinal geometries in the neutral (N) and lifted (L) sternum positions

#	Apical thoracic disc angle (°)								Apical thoracic intervertebral disc space (mm)							
	T4–T5		T5–T6		T6–T7		T7–T8		T4–T5		T5–T6		T6–T7		T7–T8	
	N	L	N	L	N	L	N	L	N	L	N	L	N	L	N	L
1	2.2	5.1	2.0	4.8	2.8	4.7	1.8	4.3	3.3	4.0	3.2	4.5	3.0	3.9	3.3	3.8
2	1.2	4.4	1.4	5.5	1.9	4.9	1.7	4.3	2.9	3.6	2.9	3.7	3.1	3.7	2.6	3.5
3	2.8	4.2	1.3	4.7	1.4	4.5	1.1	3.9	2.8	3.8	3.0	4.4	3.0	4.6	3.2	4.8
4	0.6	5.8	0.9	4.6	2.2	4.6	0.8	3.3	2.8	3.9	2.7	3.5	3.1	3.8	3.3	4.3
5	2.3	4.4	1.4	4.5	1.4	4.5	2.4	6.5	3.2	3.8	3.4	5.0	3.4	4.5	3.4	4.8
6	2.1	4.8	1.7	3.1	1.8	3.1	1.1	3.8	3.5	4.8	3.7	4.6	3.9	5.2	3.2	5.1

Fig. 3 Vertical and horizontal displacement of optoelectric sensors between radiographic positions for subject #4

1.7° ($\pm 0.6^\circ$) to 4.5° ($\pm 0.8^\circ$) and the average intervertebral disc space increased from 3.2 mm (± 0.3) to 4.2 mm (± 0.5). The values for individual discs are summarized in Table 2.

The results for the motion capture are represented graphically in Fig. 3 for the representative case of subject #4. Both the SVD jack and ribcage markers were displaced at 15° from the vertical; while the jack moved a total of 15 cm, the ribcage moved only 8 cm. It can also be noted that the subject's hip remained relatively fixed (<3 cm of

distal translation) and there was a 6 cm distal–posterior displacement of the head which included approximately 3 cm of vertical lifting.

The average and peak interface pressures for the sternum cushion in the raised position were, respectively, four and six times higher than for the thoracic cushions in the neutral position with the FSA maximum reading of 300 mmHg being reached for the sternum cushion in the raised position. A zero pressure reading was obtained for the thoracic cushions in the sternum raised position, confirming that the subjects were completely lifted up off of them. The pelvic cushion interface pressures were not impacted by the raising of the sternum. The results of the average interface pressure measurements for all subjects are summarized in Table 3 with the minimum and maximum values for each case in brackets.

Discussion

The SVD significantly increased kyphosis, as was desired, and had the consequent effect of increasing lordosis although this increase was relatively less. Examination of the radiographs shows that it was the anterior–posterior displacement of the kyphotic apex which led to the increase in kyphosis and not a global displacement of the torso. It is believed that simply raising the thoracic cushions would lead to the anterior–posterior displacement of the entire thoracic cage and have less of an impact on kyphosis. Further, if the anterior displacement was at the proximal

Table 3 Average (min–max) interface pressure measurements for all subjects in the neutral and raised positions

Position	Sternum cushion interface pressure (mmHg)		Thoracic cushions interface pressure (mmHg)		Pelvic cushions interface pressure (mmHg)	
	Average	Peak	Average	Peak	Average	Peak
Neutral	Absent	Absent	26 (23–31)	52 (41–75)	36 (30–45)	129 (73–167)
Raised	111 (44–200)	300 ^a	Not in contact	Not in contact	34 (26–47)	113 (47–164)

^a Limit reading of FSA

level of the thoracic cage resulting in a back hyper-extended position, as seen with the Böhler [9] fraction reduction and Scaglietti et al. [10] spondylolisthesis reduction techniques, the resultant would actually be a reduction of kyphosis.

The subjects in this study were free of any pathology that would impact spinal flexibility such as scoliosis and hyper-kyphosis. Although no strong correlation was found between the flexibility measurements taken on the test subjects and their increase in kyphosis in the SVD raised position, it is possible that stiff spines would experience less kyphosis increase with the SVD. The current study is a proof of concept showing that thoracic intervertebral disc space and kyphosis can indeed be increased by operative positioning. The next steps remain to validate the SVD for patients with spinal pathologies and utilize it in an operative setting.

The utility of a device such as the SVD is in its ability to increase intervertebral disc space in the thoracic region thus allowing better access to the discs and posterior vertebral elements. This can be beneficial for decompression maneuvers such as in discectomy, laminectomy, corpectomy, osteophyte removal, and foraminectomy procedures. This concept can also be exploited in order to reduce hypo-kyphosing effects that are seen in instrumentation procedures [11] or to restore a more natural sagittal balance to patients with a hypo-kyphotic scoliosis [12]. The SVD could be used to slightly raise the sternum off the thoracic cushions during final instrumentation and fusion of thoracic vertebrae in order to ensure that the desired degree of kyphosis is obtained. The exact amount of sternum elevation would be left up to the surgeon's discretion depending on the amount of kyphosis that they wish to induce for that particular patient and procedure. The maximum elevation obtainable on the current SVD prototype is 20 cm.

The difference found in the vertical displacement of the SVD and ribcage was due to two factors: cushion compression and ribcage compression. While the majority of the difference was due to cushion compression, a small ribcage compression was also observed. While it is possible that ribcage compression decreased lung capacity, none of the subjects experienced difficulty breathing when in the raised position for a period of approximately 5 min.

The MFPP included a head cushion that could slide along its longitudinal position. This avoided straining the subjects' necks while in the sternum raised position due to the observed 6 cm distal displacement of the head. It is suggested that anytime a SVD type device is used, the patient's head be allowed to move, either by surgical frame design or repositioning by the surgical staff. There were no special considerations to be taken for the positioning of the arms or lower extremities as they experienced minimal movement.

The increase in interface pressures found in the sternum raised position can be explained by the decrease in cushion contact area (the thoracic cushion contact area of 249 cm² being completely transferred to the sternum cushion contact area of 195 cm²) and by the difference soft tissue covering the sternum relative to the pectoral region. While it is possible to increase the area of the SVD cushion, doing so will reduce the effect of apical thoracic segment posterior translation. Supplemental testing in which an 84 kg male was kept in the raised position for 30 min resulted in no respiratory difficulties and minor reddening of the skin primarily where the lateral edges of the cushion interfaced with the pectoral muscles. As such, a general recommendation is that SVD use be limited to 30 min. If a longer use is required, then the patient could be intermittently lowered back onto the thoracic cushions and inspected.

Conclusion

Raising the sternum using a SVD type device allows for the significant increase of thoracic kyphosis intra-operatively. Its use should only be limited to a short period of time due to its increase in interface pressures and possible decrease in lung capacity.

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