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Original Investigation

Spine and Peripheral Nerves

Lumbar Function and Muscle Preservation Following Hybrid Surgery Versus Selective Thoracic Fusion in Adolescent Idiopathic Scoliosis: A Preliminary Comparative Study

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ABSTRACT

AIM: To investigate lumbar motion and muscle change following hybrid surgery in adolescent idiopathic scoliosis (AIS).

MATERIAL and METHODS: We conducted a prospective study design including 16 patients (14 female, 2 male) who underwent either hybrid surgery or selective thoracic fusion surgery (STF) for AIS. Trunk extensor and flexor muscle strength and endurance were assessed using an isokinetic dynamometer. Range of motion (ROM) of the lumbar region was measured by a dual inclinometer. Muscle mass was calculated by evaluating the paraspinal muscles at the L2 and L5 vertebral levels in T2W axial sections of the magnetic resonance imagings. The degree of fatty degeneration was assessed by the Goutallier classification.

RESULTS: The hybrid group comprised eight female patients with a mean surgical age of 14±1.7 years and a mean follow-up time of 16.4±8.8 months. The STF group included eight patients (six females, two males) with a mean surgical age of 14.6±1.8 and a mean follow-up time of 29.5±15.4 months were included. No significant difference was observed between the lumbar ROM, trunk flexion–extension strength, and endurance ($p>0.05$) of both groups. Similarly, no significant difference was observed between the paraspinal muscle cross-sectional area and the degrees of fatty degeneration in the patient's preoperative and last follow-up. Moreover, no differences were observed in the overall Scoliosis Research Society-22 scores between the two groups ($p=0.442$).

CONCLUSION: These preliminary findings show that hybrid surgery preserves lumbar motion and does not cause iatrogenic damage to the paraspinal muscles, including the psoas major.

KEYWORDS: Vertebral body tethering, Selective thoracic fusion, Hybrid, motion-preserving surgery, Cross-sectional area

ABBREVIATIONS: VBT: Vertebral body tethering; **PSF:** Posterior spinal fusion; **AIS:** Adolescent idiopathic scoliosis; **STF:** Selective thoracic fusion surgery; **ROM:** Range of motion; **LIV:** Lowest instrumented vertebra; **MRI:** Magnetic resonance imaging; **ODI:** Oswestry Disability Index; **CSA:** Cross-sectional area; **CVMI:** Cervical vertebral maturity index; **SRS-22:** Scoliosis Research Society-22; **CI:** Confidence interval

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INTRODUCTION

Fusion surgery with posterior instrumentation is the gold-standard surgical method for treating adolescent idiopathic scoliosis (AIS), demonstrating low complication rates and successful radiological results (14). Despite these advantages, long-term problems related to fusion surgery may occur (20). These negative effects are more common when the mobile lumbar region is included in the fusion area (22,31). Selective fusions reduce the fusion level, thereby preserving lumbar mobility as much as possible. In selective fusion, fusion surgery is applied to the major curves, while the other curves are left to resolve spontaneously (17). However, this technique carries the risk of estimating the residual deformity or adding to the existing deformity.

Non-fusion methods for controlling the curvature in AIS avoid fusion surgery problems. Some of these methods are growth-friendly approaches applied until bone maturation is achieved and ultimately result in fusion (9). Vertebral body tethering (VBT) allows both spine movement and keeps the curvature under control. It is described as a promising method in preadolescent patients (7,10). After the successful results obtained in studies on pigs, numerous case series regarding VBT were published. While VBT is a safe and effective treatment for thoracic and thoracolumbar idiopathic scoliosis based on approximately a decade of experience, researchers have raised concerns regarding the challenges in curve control post-VBT, including tether overcorrection and breakage, leading to elevated reoperation rates (15,33,34).

While VBT was initially described as a motion-preserving technique for skeletally immature patients with growth potential, recent reports indicated that its use gradually expanded to include skeletally mature adolescents and even selected adult cases, particularly for the lumbar curves. Consequently, hybrid systems incorporating posterior spinal fusion (PSF) for the less mobile thoracic region and VBT for the lumbar spine have recently emerged. This novel system allows for excellent three-dimensional (3D) correction in the thoracic region with PSF while preserving relative mobility in the lumbar segments with VBT (5).

The most important advantage of VBT over fusion surgery is the preservation of the arc of motion. Another advantage of VBT is its minimally invasive nature that reduces the risk of injury to the posterior paraspinal muscles (16). However, during anterior vertebral surgery (e.g., VBT), the psoas muscle, which is a large muscle located on either side of the spine in the lower back, may be affected (8). In clinical studies that evaluated the VBT results for the thoracic region, the thoracic region's mobility was preserved (28). Another study applied double-sided VBT and showed that the arc of motion was better compared to fusion surgery (29). However, no study has yet been conducted to evaluate the lumbar muscle structure and the range of motion (ROM) in patients undergoing a hybrid procedure.

The primary objective of this study is the comparison of the qualities of life, trunk muscle strengths and endurance, and ROM in the lumbar region between two groups of patients with AIS. One group underwent selective thoracic fusion surgery (STF), a known technique for preserving the lumbar ROM, while the other underwent a hybrid procedure. Our secondary objective is the investigation of the effects of the hybrid procedure on the paraspinal muscle morphology.

MATERIAL and METHODS

Study Design and Sample

This work is a case–control study. The literature provides no clear information regarding the sample size of our study; therefore, the sample size cannot be calculated. The study population comprised patients who underwent surgery at our center between 2021 and 2023. Patients who underwent hybrid surgery with a minimum follow-up of 1 year were included. Lenke 1C, 3C, 5C, and 6C patients were included in the hybrid group. The lowest instrumented vertebra (LIV) above L3 was excluded because it was intended to study the effect of VBT on the lumbar region. Patients with a history of previous spinal surgery or spondylolisthesis were excluded, considering that these conditions could affect the quality of life and functional outcomes. We compared the outcomes of the VBT group by selecting an age–gender and minimum follow-up duration-matched STF group from the cases operated in the same institution by the same surgical team. Lenke 1B and 1C patients were included in the STF group (Figure 1).

Patient Selection Criteria

The patient selection for STF in our center was based on the Moe criteria. STF was recommended in cases with a thoracic-to-lumbar (T/L) apical vertebral translation ratio greater than 1.2, thoracic apical rotation exceeding 20°, and a T/L Cobb angle ratio above 1.2 in the absence of thoracolumbar junctional kyphosis. Currently, there is no consensus in the literature regarding lumbar VBT indications. In our practice, VBT was considered as a lumbar fusion alternative when the lumbar deformity was flexible. The radiological criteria included a lumbar Cobb angle below 60° with at least 50% correction on the side-bending radiographs. The patient's preference and expectations also played a significant role in the treatment decision. Hybrid surgery was generally performed in patients who were unwilling to accept residual lumbar asymmetry following STF. All patients and families were informed about the potential complications and limitations of each technique. The treatment allocation was finalized through a shared decision-making process (Figure 1).

Surgical Technique

The intraoperative objective of the STF group was to achieve a residual main thoracic curve of ≤10–15° on coronal fluoroscopy while maintaining overall coronal and sagittal alignment. A correction was performed using a combination of rod derotation, segmental translation, and compression–distraction maneuvers, giving particular attention to preserving the lumbar curve flexibility and preventing a junctional malalignment. The instrumentation levels for VBT were selected as "Cobb-to-Cobb." In the hybrid group, lumbar VBT was performed first in the lateral decubitus position, followed by posterior thoracic fusion. The intraoperative aim was to achieve the maximum Cobb angle correction. A reduction to less than 10° was ob-

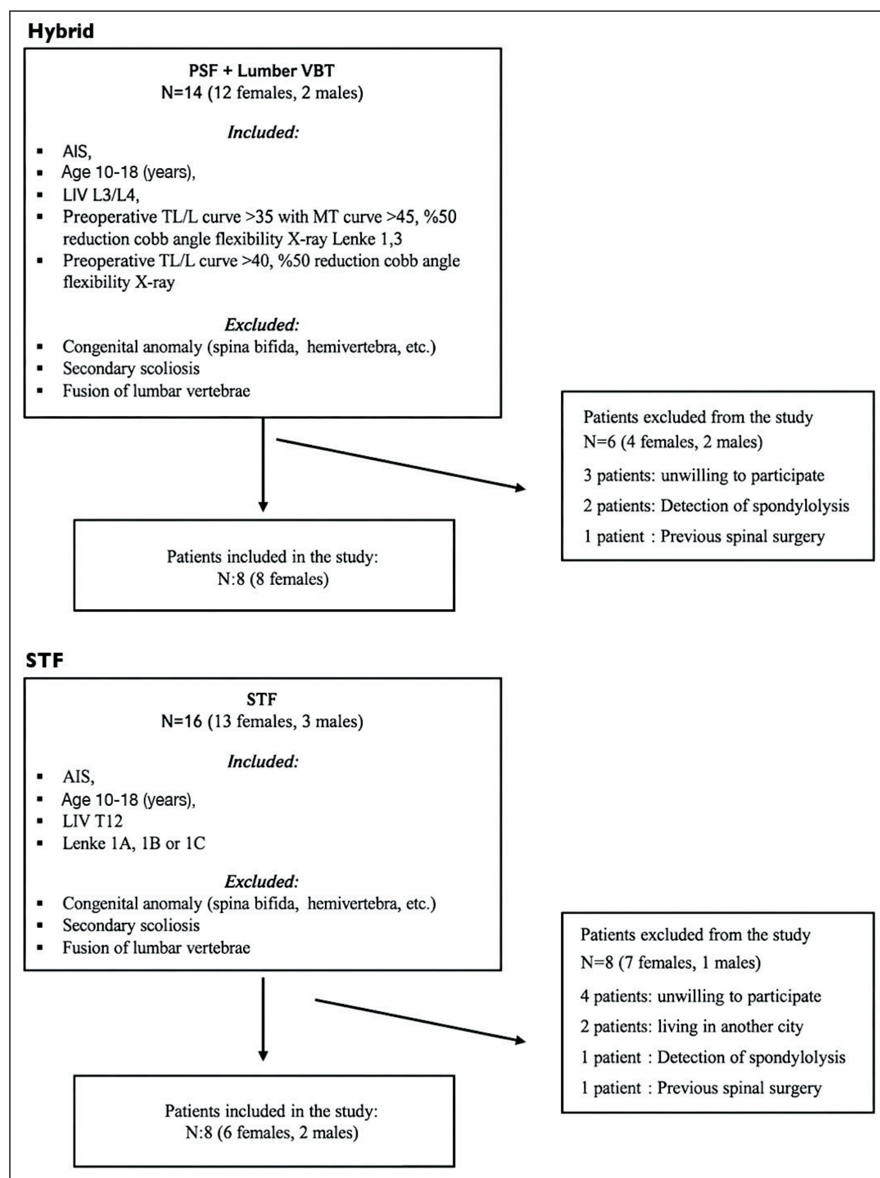

Figure 1: Study population flowchart.

PSF: posterior spinal fusion, **VBT:** vertebral body tethering, **AIS:** adolescent idiopathic scoliosis, **LIV:** lowest instrumented vertebra,**TL:** thoracolumbar, **L:** lumbar, **MT:** main thoracic, **STF:** selective thoracic fusion surgery

tained in the lateral decubitus position of all patients before proceeding to posterior instrumentation.

A single cord and one screw per vertebra were used in the first three hybrid cases. Based on the evolving literature and surgical experience, our routine technique was subsequently modified to employ a double screw–double tether configuration for each level, except for the cranial transitional vertebra. As stated, the instrumentation levels were generally selected from Cobb-to-Cobb. For STF, the LIV was chosen as the neutral and stable vertebra as defined by the central sacral vertical line. One anterior screw and two posterior pedicle screws were typically applied at the transitional vertebra.

Ethical Considerations and Data Collection

Our study was approved by the Ethics Committee of Istanbul University, Istanbul Faculty of Medicine (No: IU2022/272). All procedures were conducted in accordance with the Declaration of Helsinki. The trial was registered at ClinicalTrials.gov (NCT05347056; registration date: April 26, 2022). Following ethical approval, follow-up magnetic resonance imaging (MRI) scans were conducted during the patients' first year after surgery or at subsequent visits, contingent upon the consent of both patients and parents for their participation in this work. Written informed consent was obtained from all the participants and their parents. The data collection for the clinical outcome measures was performed prospectively as patients applied.

Outcome Measures

Clinical Evaluation

The Scoliosis Research Society-22 (SRS-22) and the Oswestry Disability Index (ODI) questionnaires were used to evaluate the clinical quality of life and the functional outcomes of the patients included in this study. The clinical measure-

ments were made by an experienced sports physician using an isokinetic dynamometer and a dual inclinometer. The "Cybex Norm" (CSMI, Stoughton, MA, USA) isokinetic dynamometer was used to evaluate the trunk extensor and flexor muscle strengths and endurance (17,24). The measurements were taken at −10° to 45° joint ROM for the trunk and at 60°/s (strength) and 120°/s angular velocities (endurance). From the results obtained, the peak torque and peak torque values per kg at 60 and 120°/s were evaluated for both flexion and extension.

The lumbar region ROM was measured using a dual inclinometer (Acumar, Lafayette Instrument, Lafayette, IN, USA). During the measurements, the main inclinometer unit was placed in the T12 spinous process. The auxiliary unit was placed in the S1 spinous process (11) (Figure 2). The patients were asked to stand upright while the flexion and the extension were measured. For the flexion measurement, the patients were asked to bend forward as far as they could without bending their knees. For the extension measurement, the patients were asked to take their trunk as far as possible from the neutral position without bending their knees. For the right–left lateral flexion measurements, the patients were asked to bend sideways without lifting their feet from the ground or leaning forward while standing upright. For the rotation measurements, the patients were asked to bend forward 90° without bending their knees. An inclinometer was placed at the previously mentioned reference points. The patients were then asked to rotate left and right.

Radiological Evaluation

The curvatures were measured by an experienced spinal surgeon who used the Cobb method and Surgimap software in all spinal anterior–posterior and lateral radiographs that were taken preoperatively, first erect and at last follow-up. The skeletal maturity in both groups was assessed through Risser staging. In addition, the cervical vertebral maturity index (CVMI) and the triradiate cartilage status were evaluated.

For the evaluation of paravertebral muscle changes, preoperative MRI and postoperative MRI with metallic artifact suppression sequence (Metal Artifact Reduction Software)

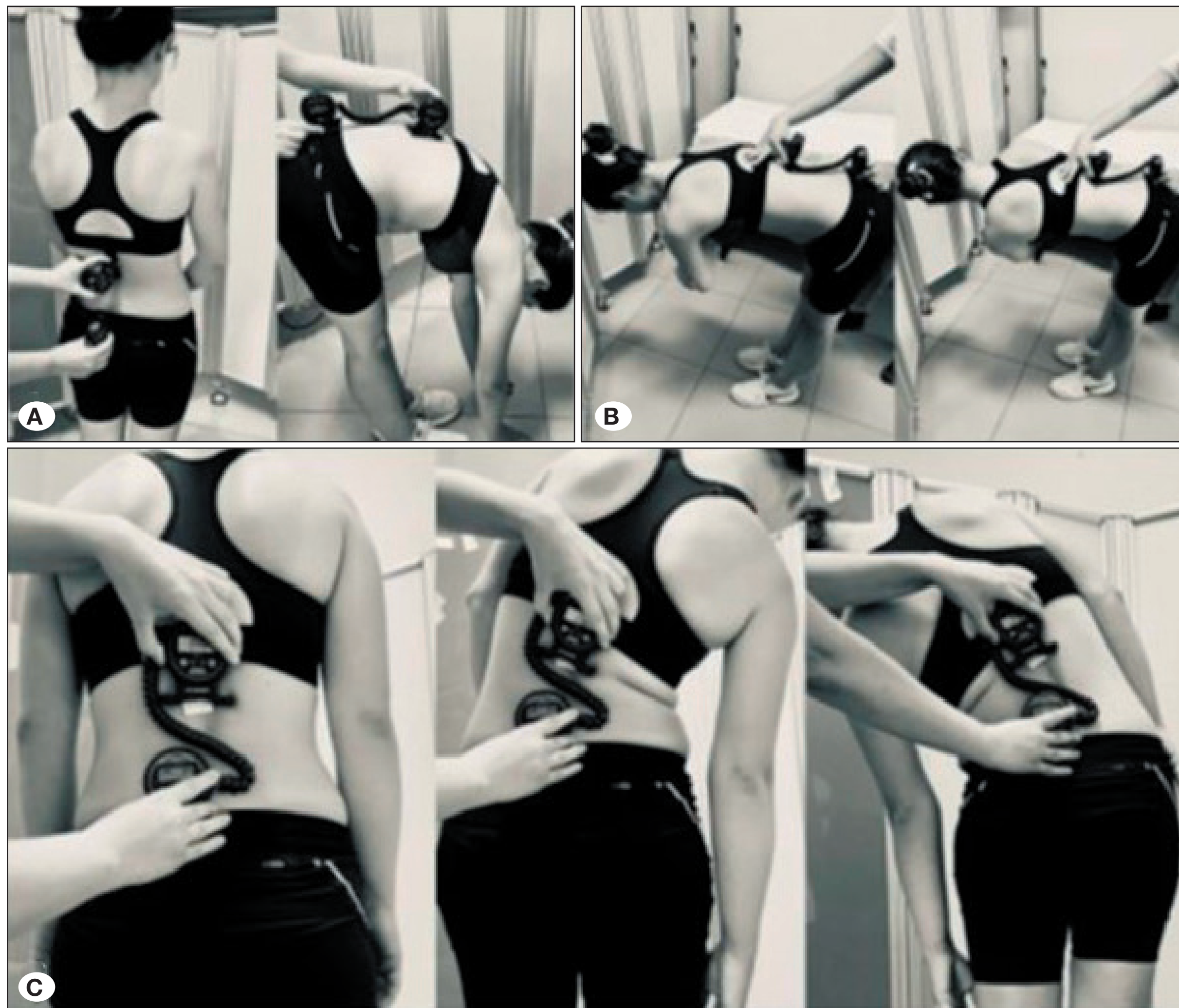

Figure 2: Lumbar spinal motion measurements using an inclinometer: **A)** flexion, **B)** rotation, and **C)** lateral flexion.

were used. The cross-sectional areas (CSAs) of the individual paraspinal muscles (i.e., multifidus, erector spinae, and psoas major) were evaluated on the T2A axial sectional images from the L2 and L5 vertebral corpus plateau superior (Figure 3). At the same time, the CSAs of the vertebral corpus were measured. We analyzed the CSA ratio to reduce the bias arising from the differences in individual body size, disk pathology, and potential patient growth during the follow-up period. This was performed by comparing the sizes of each muscle to the vertebral body (individual muscle CSA/vertebral body CSA) and expressing it as a percentage. The muscle and vertebrae corpus contours were carefully outlined. Their areas were measured independently by two musculoskeletal radiologists. The CSAs were measured in mm^2 using Extreme PACS Client (Ankara, Turkey). The Goutallier classification was employed to evaluate the degree of fatty degeneration in the lumbar region muscles (Grade 0: no fat; Grade 1: fatty streaks; Grade 2: muscle > fat; Grade 3: muscle=fat; and Grade 4: muscle < fat) (4).

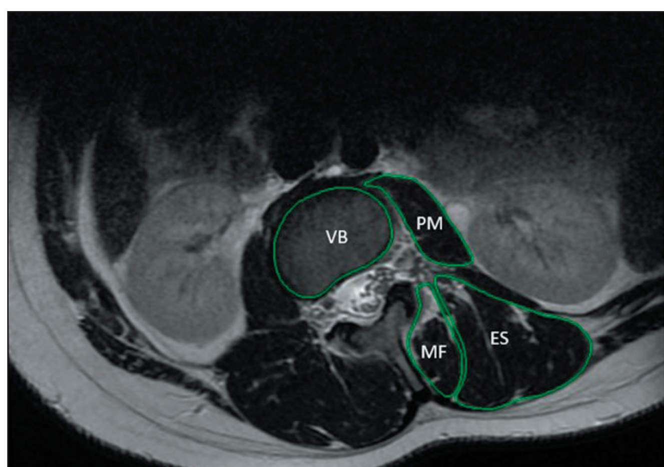

Figure 3: Measurements of the vertebrae body (VB) and the muscle cross-sectional area (CSA). CSA measurements comprised the psoas major (PM), erector spinae (ES), and multifidus (MF).

Statistical Analysis

The Shapiro–Wilk test was used to assess the normality of continuous data, confirming that the normality assumption was met. The chi-square test was performed to compare the categorical data and treatment methods. Independent sample *t*-test was used to compare the continuous data and treatment methods. The repeated measures analysis of variance was used to compare the differentiations of the presurgical post-control change between the surgical treatment methods. The McNemar chi-square test was employed to evaluate the categorical differences before the surgery post-control. The statistical significance level (α) was determined as 0.05 ($P < 0.05$). In addition to the statistical significance, 95% confidence intervals (CIs) were calculated. The clinical relevance was assessed by using the effect size analyses (Hedges' *g*) for key outcomes, including Cobb angles, lumbar ROM, and isokinetic trunk muscle strength. All statistical tests were performed using SPSS software for Windows version 12.0 (SPSS, Chicago, IL, USA).

RESULTS

Eight female patients with a mean surgical age of 14±1.7 and a mean follow-up time of 16.4±8.8 months were included in the hybrid group (Table I, Supplementary Table I). The most proximal and distal VBT instrumentation levels were T12 and L4, respectively. The hybrid group included five patients with Lenke 1C curvature and one patient with Lenke 3C, 5C, and 6 curvatures. An average of 3.7 (3–4) tethering levels was applied to the patients. All eight patients showed a left thoracolumbar/lumbar curvature. The VBT intervention was performed from the left anterolateral. The preoperative main thoracic curvature Cobb angle was 51°±6°, whereas the thoracolumbar/lumbar curvature Cobb angle was 46°±5°. The last follow-up thoracic curvature Cobb angle was 10°±6°, whereas the thoracolumbar/lumbar curvature Cobb angle was 11°±5° (Table I; Figure 4). The postoperative "first erect" radiographs were available for all patients. In the hybrid group, the mean thoracic curve changed by 4°±3°, and the lumbar curve changed by 2°±4° between the first erect and final follow-up. No complications

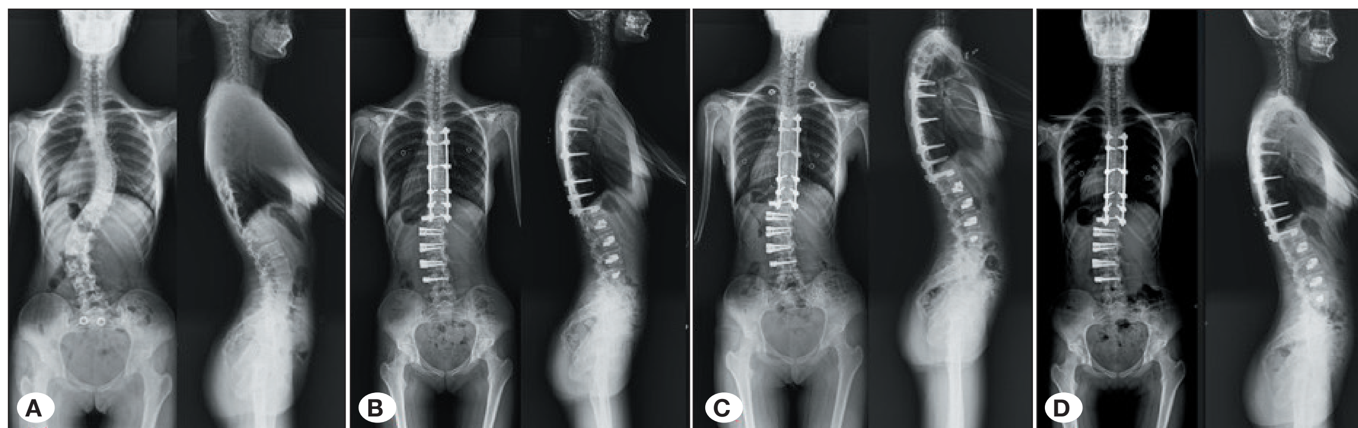

Figure 4: A) Preoperative, **B)** first erect, **C)** 6-month, and **D)** last follow-up standing anteroposterior and lateral orthoroentgenograms of an adolescent idiopathic scoliosis patient undergoing treatment for hybrid surgery.

Table I: Demographic and Radiographic Data of the Study Population

	Hybrid (n=8)	STF (n=8)	p-value	Hedges' g	95% CI
Follow-up, Mean±SD (months)	16.4±8.8	29.5±15.4	0.065		
Female Sex, n (%)	8 (100.00)	6 (75.00)			
Age, Mean±SD (years)	14 ±1.7	14.6±1.8	0.442		
Risser Score, Median (Range)	4 (0-5)	4 (2-5)			
Triradiate cartilage closed, n (%)	8 (100)	8 (100)			
CVMI Score, Median (Range)	5 (2-6)	5 (3-6)			
Lenke Classification					
1A n (%)	-	4 (50.0)			
1B n (%)	-	2 (25.0)			
1C n (%)	5 (62.5)	2 (25.0)			
3C n (%)	1 (12.5)				
5C n (%)	1 (12.5)	-			
6C n (%)	1 (12.5)	-			
Levels Tethered, Median (Range)	3.7 (3-4)	-			
Levels Fusion, Median (Range)	7.1 (6-10)	9.5 (8-10)			
LIV					
L3 n (%)	6 (75.0)	-			
L4 n (%)	2 (25.0)	-			
T12 n (%)	-	8 (100.0)			
Preoperative MT curve$^{\Phi}$ Mean±SD (Range)	51±6 (41-62)	51±10 (40-68)	0.872	0.00	[-0.98, 0.98]
First erect MT curve$^{\Phi}$ Mean±SD (Range)	8±3 (4-12)	11±4 (6-20)	0.109	–0.81	[–1.83, +0.22]
Last follow-up MT curve$^{\Phi}$ Mean±SD (Range)	10±6 (3-20)	14±7 (5-26)	0.727	-0.58	[-1.583, 0.423]
Change in MT curve$^{\Phi}$ (First erect – Last follow-up) Mean±SD (Range)	4±3	3±3	0.871	0.32	[–0.67, +1.31]
Preoperative L/TL curve$^{\Phi}$ Mean±SD (Range)	46±5 (38-51)	35±8 (29-50)	**0.027***	1.56	[0.422, 2.697]
First erect L/TL curve$^{\Phi}$ Mean±SD (Range)	9±3 (6-14)	12±8 (1-28)	0.351	–0.46	[–1.45, +0.54]
Last follow-up L/TL curve$^{\Phi}$ Mean±SD (Range)	11±5 (1-18)	13±10 (0-27)	0.952	-0.24	[-1.223, 0.745]
Change in L/TL curve$^{\Phi}$ (First erect – Last follow-up) Mean±SD (Range)	2±4	1±5	0.670	**0.21**	[–0.77, +1.19]

*__n:__ number, __SD:__ standard deviation, __LIV:__ lower instrumented vertebra, __MT:__ main thoracic, __TL/L:__ thoracolumbar/lumbar, __CVMI:__ Cervical Vertebral Maturity Index. $^{\Phi}$degree, cobb angle magnitude, * p<0.05*

related to rod rupture or surgical access were observed. However, one patient's curve showed an overcorrection in the last 6 months after completing measurements for the study, and the tether was cut with revision surgery. All clinical, radiological, and MRI assessments were completed before the revision; therefore, the analyses of paraspinal muscle CSA and fatty degeneration for this patient reflected the pre-revision state. No post-revision measurements were included.

Eight patients (six females, two males) with a mean surgical age of 14.6±1.8 and a mean follow-up period of 29.5±15.4 months were included in the STF group (Table I, Supplementary Table I). The most proximal and distal fusion levels were T2 and T12, respectively. All patients in the STF group exhibited a Lenke 1B or 1C curvature. An average of 9.5 fusion levels (8–10) was applied to the patients. The preoperative main thoracic curvature Cobb angle was 49.8°±10°. The thoracolumbar/lumbar curvature Cobb angle was 35.5°±8°. The last follow-up thoracic curvature Cobb angle was 14.1°±7°. The thoracolumbar/lumbar curvature Cobb angle was 12.8°±10°. The corresponding changes in the STF group were 3°±3° for the thoracic curve and 1°±5° for the lumbar curve. No statistically and clinically significant differences were observed between the two groups in terms of the mean age at surgery (p=0.442), mean follow-up time (p=0.065), preoperative main thoracic curve Cobb angle (p=0.872), last control thoracic curve Cobb angle (p=0.727), last follow-up thoracolumbar/lumbar curvature Cobb angle (p=0.952), or the changes in the thoracic (p=0.871) and thoracolumbar/lumbar curves (p=0.670)

between the first erect and the last follow-up. The preoperative thoracolumbar/lumbar curvature Cobb angle was significantly higher in the hybrid group than that in the STF group (p=0.027). The effect size was large (Hedges' *g*=1.56, 95% CI: 0.42–2.69), indicating a clinically meaningful baseline difference between the groups (Table I; Figure 4).

Among the groups, no differences were found in the SRS-22 sub-scores (pain [p=0.328], self-image/view [p=0.442], function/activity [p=0.645], mental health [p=0.234], and treatment satisfaction [p=1.000]) and total scores (p=0.442) (Table II).

Table II: Last Follow-Up Scoliosis Research Society-22r Questionnaire (SRS-22r), VAS, ODI Scores, and Early Clinical Parameters

Parameter	Hybrid	STF	p-value
SRS22 Pain (Mean±SD)	4.4±0.65	4.1±0.62	0.328
SRS22 SI (Mean±SD)	3.9±0.70	3.6±0.73	0.442
SRS22 Function (Mean±SD)	4.6±0.25	4.4±0.45	0.645
SRS22 MH (Mean±SD)	3.6±0.91	3.3±0.65	0.234
SRS22 Satisfaction (Mean±SD)	4.1±1.01	4.2±0.7	1.000
SRS22 Total (Mean±SD)	4.1±0.59	3.9±0.47	0.442
VAS Mean (Min-Max)	1.3 (0-4)	1.2 (0-5)	0.959
ODI Mean (Min-Max)	6.1 (0-11.1)	7.6 (2-15.5)	0.442
Length of stay (days)	4.1±1.1	3.8±0.7	0.441
Return to school (days)	24.5±2.7	23.8±1.4	0.497

***SI:** self-image, **MH:** mental-health, **SD:** standard deviation, **VAS:** visual analogue scale, **ODI:** Oswestry disability index, **STF:** selective thoracic fusion surgery.*

Additionally, no significant differences were found between the two groups in terms of the VAS (p=0.959) and ODI scores (p=0.442) (Table II). Moreover, no significant differences were observed between the two groups regarding hospital stay duration (4.1±1.1 vs. 3.8±0.7 days; p=0.441) or return-to-school time (24.5±2.7 vs. 23.8±1.4 days; p=0.497). In other words, the addition of lumbar VBT to STF did not prolong early postoperative recovery. Six of the patients in the VBT group stated they experienced anterior thigh pain or hip flexor weakness in the postoperative period. Only one patient stated that hip flexor weakness continued at the last follow-up (Table III). All participants had an ODI score of 20 or below.

Meanwhile, the hybrid group showed a lumbar flexion of 56.1°±5.18° and an extension of 22.1°±4.31°. The right and left lateral flexions were 17.9°±1.62° and 19.7°±1.82°, respectively. The right and left rotations were 7.2°±3.15° and 6.7°±3.52°, respectively. The SFT group depicted a lumbar flexion of 55.3°±3.67° and an extension of 22.5°±3.96°. The right and left lateral flexions were 19.7°±2.42° and 19.9°±2.66°, respectively. The right and left rotations were 7.2°±3.15° and 7.1°±3.80°, respectively. No statistically and clinically significant differences were found in these values between the two groups (p>0.05) (Table IV).

Based on the isokinetic strength test findings, the effect size analyses revealed small to moderate values (Hedges' *g*=0.2–0.7) for the strength and endurance measures. In line with the non-significant p values (p>0.05), the differences between the groups were not clinically meaningful (Supplementary Table II).

No significant difference was observed between the CSA ratio and the fatty degeneration of the multifidus, erector spinae, and psoas muscles before and after surgery in both groups (Tables V–VII).

Table III: Complication Rates of the Study Groups

Complication	Hybrid (n=8) n (%)	STF (n=8) n (%)
Transient neurological symptoms (anterior thigh pain / hip flexor weakness)	6 (75.0)	0 (0)
Persistent neurological symptoms	1 (12.5)	0 (0)
Overcorrection	1 (12.5)	0 (0)
Rod breakage	0 (0)	0 (0)

Table IV: Data Regarding Lumbar Range of Motion

	Hybrid (Mean±SD)	STF (Mean±SD)	p-value	Hedges' g	95% CI
Flexion	56.1±5.18	55.3±3.67	0.328	+0.17	[–0.81, 1.15]
Extension	22.1±4.31	22.5±3.96	0.878	–0.09	[–1.07, 0.89]
Lateral Bending (right)	17.9±1.62	19.7±2.42	0.105	-0.83	[–1.85, 0.20]
Lateral Bending (left)	19.7±1.82	19.9±2.66	1.000	–0.08	[–1.06, 0.90]
Rotation (right)	7.2±3.15	7.2±1.68	0.442	0.00	[–0.98, 0.98]
Rotation (left)	7.1±3.80	7.5±1.62	0.279	-0.13	[–1.11, 0.85]

***SD:** standard deviation, **STF:** selective thoracic fusion surgery.*

Table V: Cross-Sectional Areas of the Paraspinal Muscles at Each L2 Vertebra Level

	Preoperative Hybrid Mean±SD	Last Follow Up Hybrid Mean±SD	p-value	Preoperative STF Mean±SD	Last Follow Up STF Mean±SD	p-value
L2 Multifidus CSA ratio (%)						
Right	23.3±5.4	23.3±5.4	0.202	26.6±5.1	26.6±5.1	0.696
Left	23.8±4.7	25.1±3.3	0.325	26.4±4.4	26.4±4.3	0.754
L2 Erector spina CSA ratio (%)						
Right	128.7±45.3	128.7±45.3	0.450	142.8±34.3	142.9±34.2	0.315
Left	130.4±47.5	130.5±47.5	0.743	139.8±29	142.8±33.6	0.367
L2 Psoas major CSA ratio (%)						
Right	33.7±11.3	33.7±11.3	0.144	33.4±9.1	33.3±9.1	0.403
Left	32.6±9.6	32.6±9.6	0.089	34.5±7.8	34.8±7.9	0.170

***SD:** standard deviation*

Table VI: Cross-Sectional Areas of the Paraspinal Muscles at Each L5 Vertebra Level

	Preoperative Hybrid Mean±SD	Last Follow Up Hybrid Mean±SD	p-value	Preoperative STF Mean±SD	Last Follow Up STF Mean±SD	p-value
L5 Multifidus CSA ratio (%)						
Right	59.2±5.8	59.2±5.8	0.341	61.5±3.8	61.6±3.8	0.710
Left	60.5±6.4	60.6±6.4	0.142	61.4±4.3	61.5±4.2	0.707
L5 Erector spina CSA ratio (%)						
Right	68.7±17.3	69.6±17.0	0.341	84.7±13.4	84.8±13.6	0.754
Left	68.2±15.8	68.2±15.8	0.696	83.0±12.9	83.1±13.0	0.792
L5 Psoas major CSA ratio (%)						
Right	70.9±14.7	70.9±14.7	0.244	80.9±12.0	80.9±11.7	0.877
Left	70.2±4.5	70.2±4.5	0.476	85.2±19.0	85.3±18.8	0.734

***SD:** standard deviation*

Table VII: Preoperative and Last Follow-Up Fatty Atrophy of The Paraspinal Muscles According to The Goutallier Classification

	Preoperative Hybrid Goutallier Grade 1* (%)	Last Follow Up Hybrid Goutallier Grade 1* (%)	Preoperative STF Goutallier Grade 1* (%)	Last Follow Up STF Goutallier Grade 1* (%)
Multifidus				
Right	25	25	37.5	37.5
Left	25	25	37.5	37.5
Erector spina				
Right	25	25	37.5	37.5
Left	25	25	37.5	37.5
Psoas major				
Right	0	0	0	0
Left	0	0	0	0

**None of the muscles had atrophy higher than Goutallier Grade 1.*

DISCUSSION

Anterior VBT is a surgical technique that has become popular in recent years because it is thought to prevent the functional complications caused by spinal fusion (30). Although VBT is recommended in patients with growth potential, its use in adult patients has also been increasing (3). With the VBT technique, contrary to the fusion technique, the biomechanics of the spinal functional unit, which is the smallest functional unit of the vertebral column, are preserved. Iatrogenic damage to the posterior paraspinal muscles is also thought to be minimized by anterolateral intervention instead of posterior surgery. Therefore, the ideal realization of movement and load distribution (shock absorption), which are the main functions of the vertebral column, can be ensured. Furthermore, the development of the adjacent segment disease can hopefully be prevented in the long term.

As the tethering technology advances, surgeons are facing the challenge of balancing the advantages of motion preservation against the potential for increased complications or the need for further surgery (5). In VBT, the primary complications include tether breakages and overcorrection. In contrast, these issues are not observed in the PSF group. The tether breakage risk is increased in cases involving larger, lumbar, and rigid curves (2). In addition to these clinical considerations, note that VBT generally requires a longer operative time, additional operating room resources, and a specialized instrumentation system that is more costly than conventional fusion implants. These factors may increase the institutional resource utilization compared with PSF and must be considered during treatment planning.

STF is a surgical method frequently used in patients with major thoracic curvature. Its long-term results are known. The quality of life of patients who underwent STF is similar to that of the normal population, even years after surgery (12). Although some residual lumbar curvature can be found in these patients, balanced and acceptable coronal curvatures do not have a negative effect on the daily life of the patients. Moreover, the preservation of the lumbar region's arc of motion (lumbar functional units) is clinically important in the long term (25).

In patients who do not meet the selective thoracic fusion criteria and require inclusion of both the lumbar and thoracic regions in the surgical field, the hybrid procedure may offer the combined benefits of rigid fixation and motion preservation while potentially reducing the likelihood of complications and the need for reoperation. Consistent with this approach, in our series, hybrid surgery was mainly applied in cases where STF was not feasible, prioritizing lumbar motion preservation and curve correction by intraoperative techniques rather than growth modulation. Furthermore, hybrid surgery was particularly recommended in patients who were unwilling to accept residual lumbar asymmetry or deformity. Patient preference played an important role in the decision-making process. In our center, costs of both STF and hybrid surgery are fully covered by the state health insurance system; therefore, financial considerations did not influence patient preference.

This study aimed to evaluate the effect of adding lumbar VBT to selective thoracic fusion on the quality of life and the lumbar region. We performed the evaluation on patients undergoing STF and who exhibited similar lumbar curves to reduce the adverse effects from residual deformities. In this manner, the negative effects of lumbar fusion or lumbar region surgeries were eliminated from the study. The positive effects were eliminated by not including the healthy control groups without a lumbar curvature or surgical treatment. The effect of VBT on the lumbar region muscles was evaluated using presurgical and postsurgical MRIs.

VBT is introduced as a dynamic system in the literature; however, only a few studies have evaluated the functional results after VBT. Pehlivanoglu et al. reported that VBT preserves spinal mobility, based on an analysis of lumbar ROM in three planes (29). This study, which used fusion patients as the control group, demonstrated that VBT preserves motion but did not show how much loss of motion it creates in individuals who were not fused. Pahys et al. separately evaluated the thoracic and lumbar region motions in VBT and in the posterior fusion groups using a 3D motion analysis system, which is the gold-standard method for the ROM evaluation. The subgrouping was performed according to the levels at which the surgery ended (≤L1, L2, L3, and L4). The statistical analysis was performed in this manner. This study identified significantly less motion loss in patients treated with VBT in the second year after the surgery compared to the posterior fusion patients (15).

The STF group that did not undergo fusion to the lumbar region and the hybrid group that underwent VBT to the lumbar region were then compared. No statistically or clinically significant differences were observed between the two groups in all the parameters tested. The lumbar movement of the patients in both groups was within the normal range (19,27). However, the patients may possibly encounter problems as the follow-up periods get longer.

In a previous study evaluating the trunk flexor-extensor endurance in a VBT group, the VBT patients were compared with those who underwent posterior fusion surgery. The trunk flexor-extensor endurance of the VBT group was significantly superior to that of the posterior fusion surgery group (29). Therefore, we evaluated both the strength (60°/s) and the endurance (120°/s) of the trunk muscles using an isokinetic dynamometer by choosing protocols and angular velocities with proven validity and reliability during the study's planning phase. No significant differences were found between the two groups in terms of the strength and endurance of the trunk muscles. In conclusion, adding lumbar VBT to STF did not have a negative effect on strength and endurance.

The paraspinal muscle morphology is believed to play a critical role in low back pain, various spinal deformity diseases, and other pain-related pathologies (13). The postoperative morphological changes in the paraspinal muscles may affect the patient outcomes and contribute to the development of adjacent segment disease in the long term. Kumaran et al. developed a finite element model and found that the reduction in the CSA after the lumbar fusion can lead to changes in the

spinal element stresses in the adjacent segments, potentially resulting in permanent postoperative low back pain (23,32). After the spinal fusion, paraspinal muscle atrophy occurs as a result of both iatrogenic damage and loss of movement in the relevant segment (18). Lu et al. suggested that the paraspinal muscle atrophy in the thoracic region and the paraspinal muscle hypertrophy in the lumbar region may develop after STF (26). In their long-term study, Kim et al. showed a significant decrease in the CSA of the paraspinal muscles in the non-fused segment, associating this change with iatrogenic damage (21). After the usage of a dynamic system (e.g., VBT), how the paraspinal muscles involved in segmental stabilization will be affected is quite important. The only literature study evaluating the multifidus fatty degeneration and atrophy in the VBT group found that mild/moderate fatty degeneration on the concave side of the preoperative curve remained unchanged after VBT (16).

In the VBT surgical technique, the lumbar vertebrae are accessed with a mini-open retroperitoneal approach by laterally opening an oblique incision. This procedure involves a retroperitoneal dissection and a posterior retraction of the psoas muscle, although it spares posterior paraspinal muscles, such as the multifidus and the erector spinae (1). Courvoisier et al. reported that paresthesia in the proximal and anteromedial parts of the thigh is common after this surgery, even if the nerve is not damaged (6). Currently, there is a lack of research or scientific studies specifically examining the effect of VBT surgery on the psoas muscle, despite its significant role in hip flexion and lumbar spine stabilization.

In this work, no significant difference was observed in the CSA ratios of multifidus, erector spinae, and psoas at both levels (i.e., L2 and L5) in the two groups. The effect size analyses were not performed for the CSA ratios because the changes were minimal and not considered clinically relevant. In some patients under both groups, the preoperative mild fatty degeneration of the multifidus and the erector spinae remained unchanged after the surgery. In our cohort, both groups were predominantly in the late pubertal stage; however, the hybrid group included skeletally immature patients. Considering their remaining growth potential, immaturity could theoretically influence the paraspinal muscle CSA, thereby representing a study limitation. For this reason, we specifically aimed to evaluate whether or not a denervation-related atrophy developed by comparing preoperative and postoperative fatty degeneration. We found no significant difference between the preoperative and postoperative fatty degeneration grades in either group, which we considered as a valuable finding. We believe that no significant difference exists in the CSA ratio of the psoas muscle on the surgical side (left side), and that the absence of fatty atrophy signs is an important finding in the hybrid group, especially at the L2 level.

Recent studies have reported positive effects of VBT on patients' quality of life (28,29). Few studies have compared clinical outcomes of thoracic VBT (34,35). Pehlivanoglu et al. compared the posterior fusion between T5–L3 and VBT surgery performed at the same levels in the study they previously published, stating that the SRS-22 scores of the VBT group were statistically significantly higher than those of the posterior fusion group (29). Pahys et al. compared the patient SRS-22 scores between the posterior fusion and VBT groups subgrouped according to the levels at which the surgery ended. In the data obtained from this work, no differences were found in terms of the SRS-22 scores in cases where the last instrumented vertebra was L3 or above (28). The present study found no statistically significant differences between the STF and hybrid groups in terms of the SRS-22 and ODI scores. Although several patients in the hybrid group reported anterior thigh pain or transient hip flexor weakness in the early postoperative period, these symptoms resolved in most cases and did not result in significant differences in overall recovery parameters, including hospital stay or return-to-school time, when compared with the STF group. However, the only last-visit scores of SRS-22, ODI, and VAS were available, limiting our ability to evaluate the longitudinal recovery trends.

To the best of our knowledge, no studies have yet evaluated the ROM, quality of life, or muscle morphology in the patient group who underwent hybrid surgery. Cherian et al., in their study publishing early radiological outcomes following hybrid surgery, indicated that the combined PSF and VBT approach could be safe and effective for idiopathic scoliosis (5). Our results indicate that, while further studies are required, the hybrid procedure can potentially serve as a technique for maintaining lumbar mobility and avoiding iatrogenic muscle injury and does not detrimentally impact the quality of life.

Limitations

This study had certain limitations. The Lenke patient classifications were different. Although radiological correction was not the primary outcome, the curve-type distribution variability may have introduced heterogeneity and can represent a potential source of bias or confounding in the interpretation of the functional outcomes. The second limitation is that skeletal maturity was assessed without Sanders staging, which is recommended in the current literature, especially for hybrid surgery. Although Sanders staging data were available for patients in the hybrid group, some preoperative evaluations in the STF group relied on retrospective data, and hand radiographs were not consistently available; therefore, Sanders staging could not be applied uniformly across the entire cohort. However, the CVMI and the triradiate cartilage status were evaluated, both of which were considered reliable methods for the maturity assessment. All patients had a closed triradiate cartilage. The majority of patients in both groups were in the late adolescent period; however, the hybrid group included relatively more skeletally immature patients, which may have influenced the results. Another important study limitation is the relatively small sample size. With only eight patients per group, the study had limited power to detect clinically meaningful differences, consequently increasing the risk of the type II error. While the effect size analyses were performed to provide additional clinical context, the small cohort restricts the generalizability of our obtained findings. In this regard, it may be beneficial to conduct studies in more homogeneous and larger patient cohorts. Another limitation is the absence of the preoperative assessments on the quality of life

(SRS-22), disability (ODI), pain (VAS), lumbar ROM, and trunk muscle strength and endurance in patients with AIS, which limits the longitudinal assessment of functional recovery and reduces the ability to evaluate changes over time.

CONCLUSION

Probably for the first time in the literature, patients who underwent a hybrid procedure were compared herein with patients who underwent STF. VBT applied to the lumbar region preserved the lumbar region movement and did not cause iatrogenic damage to the paraspinal muscles, even on the side of the surgery. Longitudinal studies are needed to observe the long-term effects of the hybrid procedure and determine the changes in the follow-up period. Studies that include larger sample groups are needed to generalize the results.

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AUTHORSHIP CONTRIBUTION

Study conception and design: ENT, MK, GD, SK, TS, TA, BB
Data collection: ENT, MK, GD, SK, TS, TA
Analysis and interpretation of results: ENT, MK, GD, SK, BB
Draft manuscript preparation: ENT, TA, BB
Critical revision of the article: ENT, MK, GD, SK, TS, TA, BB
Other (study supervision, fundings, materials, etc...): ENT, TA, BB
All authors (ENT, MK, GD, SK, TS, TA, BB) reviewed the results and approved the final version of the manuscript.

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Supplementary Table I: Summary of All 16 Cases Included in the Study

No	Gender	Age	Risser Pre/Last	CMVI	Fusion Levels	VBT Levels	LIV	Lenke	T Cobb Pre/Last	TI/L Cobb Pre/Last	Complication
VBT1	F	15	4 /4	5/5	T5-11 (6)	T11-L3(4)	L3	5C	41/11	45/12	-
VBT2	F	12	0 /1	2/3	T7-11(4)	T11-L3(4)	L3	1C	58/12	48/1	Overcorrection
VBT3	F	14	1 /2	3/4	T4-12(8)	T12-L3(3)	L3	1C	49/3	38/7	-
VBT4	F	14	4 /4	5/5	T3-12(9)	T12-L3(3)	L3	1C	50/3	50/11	-
VBT5	F	17	5 /5	6/6	T5-12(7)	T12-L4(4)	L4	6C	47/13	50/14	-
VBT6	F	14	3 /4	4/5	T5-12(7)	T12-L4(4)	L4	1C	50/14	46/13	-
VBT7	F	15	4 /5	5/5	T2-12(10)	T12-L3(3)	L3	1C	62/20	39/18	-
VBT8	F	11	0 /2	2/4	T5-11(6)	T11-L3(4)	L3	3C	48/5	51/9	-
Mean							L3		51/10	46/11	
SD									6/6	5/5	
STF1	F	12	3 /4	4/5	T2-12(10)	-	T12	1A	44/5	30/6	-
STF2	M	14	4 /4	5/5	T2-12(10)	-	T12	1B	53/26	32/27	-
STF3	F	15	2 /4	3 /5	T4-12(8)	-	T12	1B	43/8	30/8	-
STF4	F	17	5 /5	6/6	T2-12(10)	-	T12	1A	40/8	30/0	-
STF5	F	15	4 /5	5/6	T2-12(10)	-	T12	1C	68/22	50/25	-
STF6	M	16	4 /5	5/6	T2-12(10)	-	T12	1C	59/17	48/17	-
STF7	F	12	4 /4	5/5	T3-12(9)	-	T12	1A	58/17	35/16	-
STF8	F	16	4 /5	5/6	T3-12(9)	-	T12	1A	41/10	29/4	-
Mean							T12		51/14	35/13	
SD									10/7	8/10	

***LIV:** Lowest instrumented vertebra, **SD:** standard deviation*

Supplementary Table II: Comparison of the Lumbar Strengths and Endurance Scores of Both Groups

		Hybrid (Mean±SD)	STF (Mean±SD)	P	Hedges' g	95% CI
Flexion	Peak torque at 60 °/s (Nm)	113.75±20.37	111.87±34.41	0.645	+0.06	[–0.92, 1.04]
	Peak torque at 60°/s %BW (Nm/kg)	215.88.37±33.97	182.87±65.02	0.161	+0.60	[–0.40, 1.61]
	Peak torque at 120 °/s (Nm)	84.75±22.11	68.87±20.55	0.195	+0.70	[–0.31, 1.72]
	Peak torque at 120 °/s %BW (Nm/kg)	132.75±68.60	117.00±53.01	0.574	+0.24	[–0.74, 1.23]
Extension	Peak torque at 60 °/s (Nm)	98.88±22.09	93.37±27.75	0.721	+0.21	[–0.78, 1.19]
	Peak torque at 60°/s %BW (Nm/kg)	187.75±39.73	156.75±64.11	0.195	+0.55	[–0.45, 1.55]
	Peak torque at 120 °/s (Nm)	53.38±23.71	60.37±18.66	0.442	–0.31	[–1.30, 0.68]
	Peak torque at 120 °/s %BW (Nm/kg)	101.75±44.61	102.12±45.36	1.000	–0.01	[–0.99, 0.97]

***Nm:** Newton-meter, **BW:** body weight, **SD:** standard deviation*