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Original Article

Monitoring therapy outcomes in idiopathic scoliosis patients: case series and a proposed model

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Abstract:
Introduction: Current treatment options for idiopathic scoliosis include three main strategies: physiotherapy, bracing and surgery, which are used combined or successively, but in many cases are not efficient. This study aimed to develop a targeted, efficient, and appropriately calibrated approach for continuously monitoring of scoliosis therapy. Methods: Six patients with idiopathic scoliosis (IS) participated in this consecutive sample study. The study group (n = 6) underwent a physical rehabilitation program that utilized motion capture and myometry for control.Both before and after program completion, all patients underwent X-ray revaluations. Repeated assessments of muscle thickness were conducted to establish a correlation between biomechanical spine remodeling and paraspinal muscle development. Results. Results of MoCap spinal curvature assessment correlate positively with the x-ray measurements ($f2 \geq 0.35$). The same ratio of difference in x-ray angle measurement results was revealed after the study completion ($P<0.001$). Both the muscle thickness and the body muscle mass measurements showed negative correlation with the changes in Cobb's angle measurements (the angle was decreased in all measurements, whereas the muscle thickness and mass were increased). Correlation for the SMI ($R=-0.88$) was close to -1.0. For the measurements in the study group the minimum R value was -0.92 and for paraspinal muscles L3-L4 and SMM (%) the correlation index was -0.96. These results indicate that the improved muscle thickness and muscle mass (particularly the SMM (%)) support the posture correction and assist in spinal stability. Conclusion. The MoCap and myometry controlled assessment is an efficient, safe and reliable monitoring model to control the outcomes of scoliosis rehabilitation.
Keywords: Spinal deformity, Motion capture, Ultrasound, Muscle thickness, Bracing, Assessment model

Introduction

Idiopathic scoliosis (IS) in children and adolescents is a spine deformation occurring in approximately 3% of the population with a higher incidence in girls than in boys (8:1) (Sung et al 2021). Proper and early diagnosis of this condition is a requirement to prevent the progression of scoliosis. Current treatment options include three main strategies: physiotherapy, bracing and surgery, which are frequently used, combined or successively, but in many cases are not efficient or even lead to numerous types of exacerbations: escalation of pain or motor problems (Wang et al 2020; da Silveira et al 2022).

Lateral curvature of the spine is evaluated by X-ray using the Cobb's method. IS is manifested with vertebral and trunk rotation (Laubach et al, 2023). Different strategies have been offered for the IS treatment, but brace treatment and exercise therapy are the only potentially effective tools to prevent the progression of IS curve and avoid the need for surgical intervention (Zaina et al, 2022). Various types of braces have been practically used in the practice to correct the curved spine and different exercise strategies applied to correct and preserve the altered posture (Karavidas, 2019).

The aim of brace treatment for IS is to stop the progression of scoliosis curve. Efficacy of this therapeutic approach in patients with IS has been controversial, as part of the researchers has reported a failure after bracing treatment (Cheung et al 2019). However, BrAIST (Bracing in Adolescent Idiopathic Scoliosis Trial) study has shown the effectiveness of bracing, suggesting it as an effective non-surgical method of early management in patients with IS, that reduces significantly the rate of complications and number of patients who needed surgical intervention (Lee et al 2023).

There are different forces applied to correct deformity of spine: distraction, compression, transverse forces and side bending force (Fig 1). Longitudinal forces are considered to be more efficient for larger curves, and transverse forces applied at the apex have shown to be more efficient in patients with spinal deformity of less than 50° (Sarwark et al, 2019). However, the main forces used to correct deformities are distraction forces applied on the concave side, compression forces applied on the convex side, transverse forces applied on both sides, and side bending applied on the convex side (Fig 1).

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The position of brace pads is important for the correction of deformity (Figures 1 and 2). If the thoracic pad is placed closer to the midline, the anterior force will increase, facilitating thoracic hypokyphosis, which already may exist in advanced scoliosis. If the thoracic pad is placed laterally, the force may further rotate the spine in the undesirable direction. Therefore, the location of the pad should be selected meticulously to ensure the maximum balanced and efficient influence of anterior and transverse forces on the thoracic spine. In the lumbar spine, the lumbar pad should be placed on the apex to push the transverse process from the posterolateral direction applying bending and derotational forces (Fig 2). Together with this lumbar lordosis should be reduced in brace wear.

Physiotherapeutic scoliosis-specific exercises (PSSE) are the main non-surgical treatment option for IS (Timnea Olivia Carmen et al, 2019; Natalya mischenkoet al, 2023). PSSE is an individualized and curve specific physiotherapy method. For the last three decades, a large number of studies have confirmed the effectiveness of PSSE compared to routine exercise programs and the basic advantage of PSSE is the individualized approach (Burger et al, 2019). The PSSE approach is used in different physical therapy strategies: Schroth method, Barcelona scoliosis physical therapy (BSPT), the scientific exercise approach to scoliosis (SEAS), Lyon approach and many others (Stamenka Mitova et al, 2020).

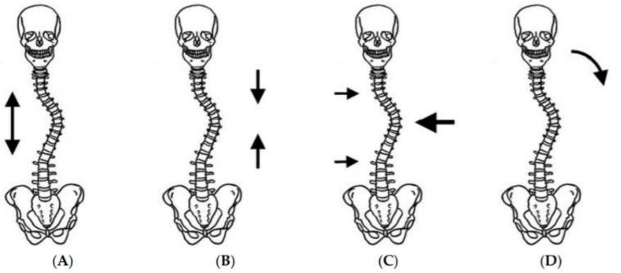

Figure 1 Forces applied to correct the scoliosis curve A) Distraction force, B) Compression force C) Transverse force D) Bending force

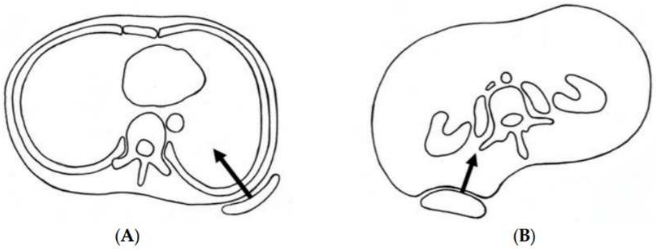

Figure 2 Position of bracing pads to induce maximum efficient forces: A) Thoracic spine B) Lumbar spine

PSSE applies stretching and strengthening exercises, breathing in reverse directions based on spinal deformation (Zhou et al, 2021; Petrosyan et al, 2021, Pesenti et al, 2019; Olena Svietlova et al, 2016). Other than exercise, the patients were informed about peculiarities of scoliosis to help them in self-postural control and to turn the improved posture into a habit (Walter et al, 2021; Alexander E. Bolotin et al, 2015).

Curve deformity angle measurement method was suggested by Cobb. The angle of curvature is determined by drawing lines parallel to the upper and lower borders of the scoliosis curve. Then perpendiculars are drawn from these lines that cross each other. The angle of scoliosis curvature is the one between these perpendiculars (Muccio et al, 2023; Haddas et al, 2020, Helenius et al, 2020).

Application of any PSSE strategy requires evaluation of patients before and after the exercise therapy intervention. Moreover, in longitudinal studies there is a need to evaluate the treatment efficacy periodically. The most reliable and clinically valuable method for the evaluation of scoliosis curve changes is the x-ray measurement of Cobb's angle (Fig. 3). The advantage of x-ray measurement is that it can provide the precise value of the Cobb's angle at the time of the measurement. This method cannot be used as a dynamic evaluation tool. Applying x-ray measurements once in three or six months may or may not prove the efficacy of the physiotherapy strategy in a patient, as not always the treatment outcome is positive and the intervention may not lead to improvement. The main peculiarity of PSSE strategy is the individualized approach, when the patient should be continuously monitored with a reliable visualization tool. X-ray measurement methods get the top scores for the reliability but they lack the ease of use, safety and cannot be applied frequently in the monitoring process. Opto-electronic motion capture (MoCap) systems are widely used in a large number of biomechanical studies. These systems are mostly used for the gait kinematics study, and there have been attempts to analyze the gait in patients with IS (Khan et al, 2023; Tigran Petrosyan et al 2019, Tigran Petrosyan et al, 2021; Schmid et al, 2015).

Exercise and particularly the bracing may result in curve regression, though this achievement should be maintained on the same level. Going through all pathognomic mechanisms and hypotheses, we may halt our pace at the theory indicating changes in muscle structure and function resulting in asymmetry of erector spinae muscles. The other theories and mechanisms are hard to modulate and positive outcome is less plausible. Eliminating the asymmetry by PSSE, which balances the muscle volume on both sides of the curve, is a goal-oriented strategy, but the question is when to start this muscle amelioration. Bracing without PSSE and routine exercise weakens the muscles and if neglected may result in significant atrophy of trunk muscles. Increase in muscle volume on the concave side contributes to the longitudinal and transverse forces that preserve the angle of regression. Therefore, the exercises are essential and should be started with bracing, but in an asymmetrical mode, putting more load on the concave or weakened side. Best and reliable way to assess the muscle volume is the B-mode ultrasound and muscle mass analyzers.

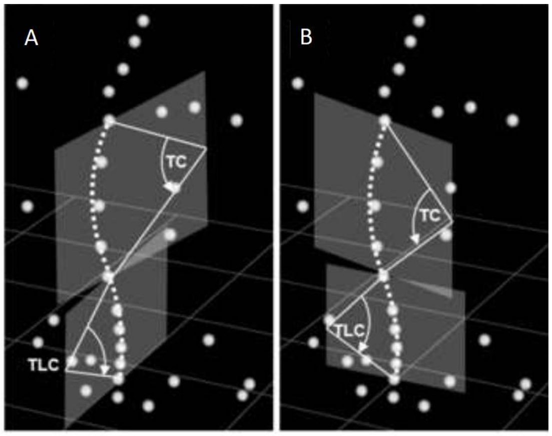

Figure 3. Thoracolumbar / lumbar (TLC) and thoracic (TC) curvature angles in the sagittal (C) and frontal planes (D).

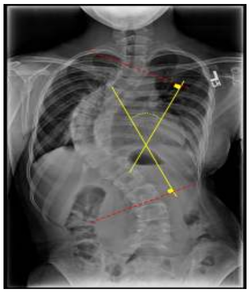

Figure 4. Cobb's angle measured on an x-ray of spine

Combining the research evidence and scrutinizing the pathophysiology of the IS, we tried to offer a time efficient, targeted intervention that can ensure the successful course and desirable efficiency of the conservative treatment. Daily (during each session) evaluation of spine biomechanics, including the curve and relationship between the spine and pelvis can assist the physiotherapists to modulate their strategy. Estimation of muscle volume is of absolute importance, but not any other muscle parameter: elasticity, electrical or reflex activity. Muscle volume undeniably provides strength and needed force, whereas the rest of parameters are rather neuromuscular, and when prescribing exercises to generate strong muscle force, cannot serve as modulating variables. Monitoring of a muscle volume (e.g. erector spine) or the general volume of paravertebral muscles supplements the optometric data, providing the intervention team a positive lead towards the fast and successful completion of the physiotherapy treatment. The goal of the study is to identify a targeted, efficient, safe and not overestimated method for the monitoring of physical rehabilitation of scoliosis.

Methods

Study participants

A consecutive sample of 6 patients with IS were involved in this study. All participants were 14-18 years old IS patients (Cobb angle of between 25 and 50^0). Inclusion criteria was the confirmed diagnosis of thoracic and a thoracolumbar curve. Exclusion criteria were locomotor system injuries, other types of scoliosis, neuromuscular disorders and previous surgical intervention of the spine, any comorbidities that may affect the locomotor system, or obesity (BMI-per-age percentile should be > 95th). Leg length was measured from anterior superior iliac spine to medial malleolus. This measurement must not show inequalities of more than 1% of body height. All legal guardians of patients agreed to sign informed consent. The patient group (n=6) underwent a motion capture and myometry controlled physical rehabilitation program including physiotherapy and bracing.

Motion capture and x-ray study

Prior to the start of the intervention program, all patients underwent a biplanar radiographic examination to measure the Cobb's angle (Scaramuzzo et al, 2022; Schmid et al, 2015). X-ray examination have to be repeated after six months when the physiotherapy intervention program was completed.

For the evaluation with motion capture system all participants were equipped with 38 retro-reflective body markers (and another set of 14 markers for legs to conduct gait analysis) that included the standard Plug-in full body and the specific spine markers by an exercise physiologist experienced in gait analysis (all measurements were performed by the same specialist). Gait and spine motion analysis was conducted using a 9 - camera motion analysis system (Qualisys Oqus 510, sampling frequency: 200- 300 Hz). According to standard standing measurement mode protocol, the study group participants were asked to walk 10m on a ground level (repeating trials for multiple times) at a self-selected speed, then to stop and stand loose in erect position with feet several inches apart for capturing. For the analysis five trials were selected and registered.

Kinematic data were processed by a biomechanics analysis software Visual3D V6 Professional. Spinal curvature was determined using the markers fixed on spinous processes. Thoracic and lumbar curves in the sagittal plain were determined in all participants. The important markers used in this process were markers from thoracic 1 to lumbar 5. These markers help to determine the thoracic and thoracolumbar or lumbar curves of the study group participants in the frontal plane. The curves were fixed by the markers that corresponded to the boundaries of Cobb-angle (Figure 3). At least four markers were used to capture each curve.

A possible projection error might be registered as the thorax rotates during gait. To avoid this error sagittal and frontal dynamic planes were registered for the thoracic curvatures using a sternal marker and the most proximal apical marker. For the thoracolumbar or pure lumbar curvatures, the same planes were identified based only on the coordinate system, as there were no special reference points for this segment (Figure 4). To calculate the curve angle based on the central angle circular segments were created using the second order polynomial function and the circle fit function. To quantify the trunk motions during gait, position and orientation of lumbar, thoracic and cervical segments as well as of the pelvis, was determined relative to the reference segments fixed in the standing trial. Relative angles between the thoracic and the pelvis segments were calculated in all planes. All angles were time standardized to the gait cycle (time between two right foot strikes). If the patient has a left sided convexity, the mirrored data of a left gait cycle was used. Angle analysis was used to remodel the gait.

Muscle thickness and mass measurements

Muscle thickness was measured using ultrasound technology at three levels on both sides of the spine: C7 –C8; Th7-Th8 and L3-L4, 20mm laterally from the central line (the line connecting spinous processes). The measurements were performed while the patients stand relaxed with their hands close to the trunk and feet together and weight evenly distributed on both legs. The transducer with a 5-MHz scanning head (Siemens Acuson P500) was coated a special water soluble transmission gel for better acoustic contact and pressure reduction. Total body muscle mass was determined by the body analyzer Tanita BC-418 MA.

Physiotherapeutic scoliosis-specific exercises program

Schroth best practice exercise program is an intensive Schroth exercise protocol. The protocol includes the following components (Natalya mischenko et al 2023).

- Physiologic exercises that target the sagittal plane.
- Mobilizations: mobilizing the spine and ribcage using passive, active, and active assistive range of motion, as well as strengthening maneuvers.
- ADLs in standing, sitting and walking for correction of frontal plane.
- 3-D Made Easy: simplified 3D scoliosis-specific corrective exercises.
- Power Schroth: advanced 3D scoliosis-specific corrective exercises.

The physiotherapy sessions were conducted three times per week. Duration of the physical rehabilitation (encompassing physiotherapy and bracing) program was 6 months.

Bracing and the applied protocol

We usually use the Boston brace for the treatment of IS. The Boston brace is the most used type in the country. This option of bracing is lightweight, provides the thoracic alignment and balance. If the patients have tolerated the brace for at least 10 hours per day, they are recommended to wear it for a longer period.

Health-related quality of life assessment

The Scoliosis Research Society-22 (SRS-22) questionnaire was used to assess health-related quality of life in all study participants.

Statistical analyses

The power of the sample size was determined using Gpower 3 statistical software. Statistical software package SPSS 21 was used for the data analysis. Intraclass correlation coefficient (ICC) was used to show that statistical calculations of the five trials per subject were consistent calculating their 95% confidence intervals. ICC values over 0.85 were considered acceptable. Differences for studied parameters were analyzed using independent samples T-tests. To show the clinical relevance of the registered differences that demonstrate considerable improvement minimal clinically important differences (MCID) were calculated (small: $d \geq 0.2$, moderate: $d \geq 0.5$ and large: $d \geq 0.8$), according to previously published research data. The registered differences were defined as A) clinically relevant (95% CI of mean difference above MCID), B) possibly clinically relevant (95% CI of mean difference contained MCID) and C) not clinically relevant (95% CI of mean difference below MCID). The relationship between the scoliosis curvature angle and degree of scoliosis from x-ray evaluation (Cobb-angle) were tested by Pearson correlation analysis. Correlations that showed considerable effects (small: $f2 \geq 0.02$, moderate: $f2 \geq 0.15$ or large: $f2 \geq 0.35$) were classified as 1) statistically significant ($p \leq 0.05$) and 2) statistically not significant ($p > 0.05$).

Data from muscle thickness and total body muscle mass in the group were analyzed with repeated measures ANOVA. Pearson correlation analysis was used to show the correlation between muscle measurements and MoCap data.

Ethical Approval The procedures with participation of humans were in accordance with the ethical standards provided by the institutional and national research committee, and were based on 1964 Helsinki declaration and the later amendments and comparable ethical standards.

Inform Consent Informed consent was obtained from all individual participants included in the study.

Results

Evaluation of patients with IS using x-ray Cobb's angle measurements and motion capture system before and after the rehabilitation program.

A consecutive sample of 6 patients with IS were involved in this study. Cobb's angle measurements by x-ray and motion capture system were obtained. The measurement data are presented in table 1. To assess the efficacy of the interventional program the measurements were repeated after 3 (intermediate testing) and 6 months (final assessment).

The MCID has been defined as "the smallest difference in score in the domain of interest which patients perceive as beneficial. MCID values are therefore important in interpreting the clinical relevance of observed changes at both the individual and group levels.

The anchor-based method to estimate MCID values uses comparison of change scores with an anchor, usually either a patient or a clinician rating of change. A benefit of the anchor-based method is that the estimate is based on changes that were considered important to the patients or clinicians.

The magnitude of change that is considered meaningful may be influenced by the spine assessment method: whether the x-ray assessment versus MoCap data were affected by the physical therapy program. Results from spine assessment with x-ray and MoCap were therefore analyzed separately. To determine the MCIDs on each measurement method, mean change scores for each perceived change rating were computed. Patients with idiopathic scoliosis participating in the program have completed SRS-22 questionnaire before and the after the study completion. MCID values for the SRS-22 were determined based on the selection of a single answer out of 5 provided for all 22 questions (1 – 5 points). Part of the questions were negative so the score 5 was given to the last question, and in positive questions the maximum score was for the first answer. Based on the standardized mean differences the effect size was determined for all 3 assessment methods: x-ray, MoCap and SRS 22 (Table 2).

Evaluation of muscle volume in patients with IS using ultrasound technology and evaluation of total body muscle mass using the analyzer before and after the physical rehabilitation program.

Muscle thickness was measured using ultrasound at three levels on both sides of the spine: C7 –C8; Th7-Th8 and L3-L4, 20mm laterally from the central line (the line connecting spinous processes). The measurements were performed while the patients stand relaxed with their hands close to the trunk and feet together and weight evenly distributed on both legs.

For each ultrasound measurement, the technician placed the transducer head longitudinally over the spinous processes and then moved the head laterally to fix the zygapophyseal joint (the transducer head to spinous process angle was 30° to 45°). The measurements were repeated three times for each point on each side.

For each participant the technician performed 2 testing procedures, with a 10-minute interval. A radiologist performed ultra sonographic measurements of obtained muscle thickness for both testing sessions to determine the interrater reliability of the ultrasound image acquisitions.

To determine the interrater reliability of ultra sonographic measurements, the radiologist and the principal investigator performed an independent analysis of muscle thickness measurements for the lumbar multifidus muscles and the deep thoracic paraspinals. In participants with idiopathic scoliosis, each side of the spine was labeled in data files as concave or convex, depending on the curve type.

The measurements of muscle thickness were performed before the exercise program. The intermediate measurement was conducted three months later and the final assessment was performed after the study completion (after six months). Data from muscle thickness measurements are incorporated in tables 1 and 4.

Total body muscle mass was determined by the body analyzer Tanita BC-418 MA. The skeletal muscle mass (SMM) and appendicular skeletal muscle mass (SMMa) were measured in all participants. Initially the SMMa values were measured and the SMM was derived using the formula SMMa/Weight x 100.

The purpose of these measurements was to show not only changes in SMM, but also to show the body distribution of muscle mass. For this purpose the skeletal mass index (SMI) was measured in participants using the formula SMMa/height^2.

Data for initial, intermediate and final assessments of muscle mass are presented in table 1.

Table 1
Comparison of data obtained at different time points.

Patient data and measurements	N=6 (Female: 3)	N=6 (Female: 3)	N=6 (Female: 3)
	Initial data	**Intermediate**	**Final results after 6 months**
Age (years)	13.60±2.24	-	-
Height (cm)	148.00±11.45	-	-
Weight (kg)	43.80±12.53	-	-
Body mass index, kg/m^2	21.2±4.8	-	-
Cobb's angle (°) x-ray	36.20±6.82	27.40±5.32	23.62±4.84
Stat. Significance			P<0.001
Cobb's angle (°) MoCap	34.60±8.42	26.10±4.86	21.40±4.12
Stat. Significance			P = 0.0014
SRS 22 scores	2.6±0.46		3.9±0.83 P=0.002

Muscle thickness	**Ultrasonographic Measurements (Mean ±SD) of Paraspinal Muscles (cm) in the Relaxed Standing Position**					
	Initial assessment		**Intermediate assessment**		**Final assessment**	
	Concave	**Convex**	**Concave**	**Convex**	**Concave**	**Convex**
C7 –C8	1.42 ± 0.32	1.29 ± 0.27	1.34 ± 0.32	1.31 ± 0.27	1.32 ± 0.24	1.34 ± 0.28
Stat. Significance					P=0.49	P=0.72
Th7-Th8	1.92 ± 0.44	78 ± 0.32	1.88 ± 0.38	1.82 ± 0.48	1.82 ± 0.22	1.86 ± 0.44
Stat. Significance					P=0.57	P=0.68
L3-L4	2.32 ± 0.48	)8 ± 0.36	2.16 ± 0.42	2.04 ± 0.44	2.10 ± 0.40	2.11 ± 0.32
Stat. Significance					P=0.34	P=0.46
Body muscle mass						
SMM (%) (SMMa/Weight x 100)	30.2±0.4		30.8±0.6		31.4±1.4	
Stat. Significance			P=0.03		P=0.04	
SMMa(kg)	15.9±0.4		16.2±0.6		16.8±0.8	
Stat. Significance			P-0.26		P=0.01	
SMI (SMMa/height^2)	6.8 ± 0.1		6.9 ± 0.1		7.2 ± 0.4	
Stat. Significance			P-0.065		P=0.02	

The statistical significance of difference in results for Cobb's angle measurements and SRS22 scores between the baseline and final assessments was determined with the T–test. Muscle thickness and total body muscle mass changes were assessed with repeated measures of ANOVA

Study of dynamic variations in scoliotic curve during gait for the remodeling of gait and constituent movement patterns to make the correct gait and posture patterns habitual

Variations in scoliotic curve during gate and changes in segmental angular data were measured to derive potential predictors of the intervention program outcomes - the correct gait and posture. In the study group patients comparison of thoracic curvature angles revealed less kyphosis (on average 11.2° (4.4°,18.3°)), yet in the sagittal plane range of motion was increased for 5.2° (2.5°,7.9°) and the lateral deviation range on the left side was 13.6° (7.1°, 18.6°). Measurements in thoracic and lumbar segments showed that the average lordosis angles were 3.8° (-7.8°,16.2°), the lateral deviation range on the right side was 24.2° (13.8°,31.6°) and the frontal angular value was 3.2° (- 1.4°,6.9°). Positive correlation was registered between the Cobb-angle and the thoracic curvature angles in sagittal plane (R2=0.6) as well as frontal plane (R2=0.5). The correlation was positive in case of the sagittal and frontal lumbar angles (R2 =0.2 and R2 =0.3). Although the sagittal average and ROM parameters of the thoracic curvature angles were categorized as possibly clinically relevant, these results were considered for the analysis due to their large effect sizes (d=1.35 and d=1.65).

The sagittal average and frontal ROM parameters of the thoracolumbar/lumbar curvature angles were not considered due to only small to moderate effect sizes. The statistically not significant correlation for the sagittal average thoracolumbar/lumbar curvature angle was not considered due to a small effect size. The angular parameters in different segments of spine and gait spatio-temporal parameters were not significantly different between the assessments. Full assessment and statistical analysis was conducted for segmental angular data after completion of the study.

Study of physical rehabilitation program (PSSE protocol and bracing) efficacy on scoliotic deformity using motion capture system for continuous monitoring of the curve and B-mode ultrasound for the muscle volume repetitive measurement

The results for the PSSE protocol and bracing were assessed based on the Cobb's angle measurements by the motion capture and ultrasound measurements of paraspinal muscles. The intermediate data were obtained from the group. The comparison of interim and final results could be a basis to assess the efficacy of the selected interventional approach. Results of intermediate and final assessments are included in table 1-4.

Results of MoCap spinal curvature assessment correlate positively with the x-ray measurements ($f2 \geq 0.35$). The group of patients treated with PSSE protocol and MoCap controlled bracing showed reduction in scoliosis curve ($P = 0.0014$). The same ratio of difference in angle measurement results after the study completion was revealed when assessed by the x-ray ($P<0.001$).

Both the muscle thickness and the body muscle mass measurements showed negative correlation with the changes in Cobb's angle measurements (the angle was decreased in all measurements, whereas the muscle thickness and mass were increased). Correlation for the SMI (R=-0.88) was close to -1.0. For the measurements in the study group the minimum R value was -0.92 and for paraspinal muscles L3-L4 and SMM (%) the correlation index was -0.96.

These results indicate that the improved muscle thickness and muscle mass (particularly the SMM (%)) support the posture correction and assist in spinal stability. The targeted physical rehabilitation, with targeted exercises addressing the instability in spinal segments described in previous chapter is potentially effective approach for scoliosis management. This results show that targeting the spinal segmental instability was superior to muscle strengthening alone. The increased muscle mass and thickness do play a significant role in curvature reduction, yet the treatment efficacy was much higher when addressing the segmental instability. Both the PSSE and routine exercise therapy resulted in posture improvement. However, the better results obtained in the patient group were due to targeted exercises for spinal segments with instability and the bracing with higher pressure force over the non-stable spinal (thoracic) segments.

Table 2

MCID expressed as Effect sizes derived from standardized mean differences

	Cobb's angle (°) x-ray	**Cobb's angle (°) MoCap**	**SRS 22 scores**
MCID	d = 2.13 CI=0.90 and 3.35	d-1.99 CI=0.79 and 3.19	d= 1.9 CI=0.75 and 3.13
Difference size	Large; Clinically relevant	Large; Clinically relevant	Large; Clinically relevant

Table 3

The relationship between the scoliosis curvature angle and degree of scoliosis from x-ray evaluation (Cobb-angle) tested by Pearson correlation analysis.

	Cobb's angle (°) MoCap
Cobb's angle (°) x-ray	R=0.96 $f^2 \geq 0.35$

$p \leq 0.05$

Table 4
Pearson correlation analysis between muscle measurements and MoCap data for the study group

	Paraspinal Muscles C7 –C8 convex	Paraspinal Muscles Th7-Th8 convex	Paraspinal Muscles L3-L4 convex	SMM (%)	SMMa(kg)	SMI
Cobb's angle (°) MoCap	R=-0.97	R=-0.94	R=-0.96	R=-0.96	R=-0.94	R=-0.92

Discussion

This study had a purpose to analyze the spinal kinematics for the study participants with scoliosis in gait and to provide evidence of effective therapy monitoring with kinematic data. The obtained results showed biomechanical differences in the sagittal and frontal planes, changes in Cobb angle in thoracic spine segment in the sagittal plane. We tried to use some of the spine kinematic parameters focusing on the angular parameters between thoracic and pelvic segments. The spine model that we have suggested in the study helps to monitor clinically relevant parameters in patients with deformities of spine in gait.

The patients in the study group showed reduced degree of thoracic kyphosis angles during gait. Usually the diminished thoracic kyphosis is caused by the progressing scoliotic curvature. As this thoracic kyphosis angle is a measurable parameter, it is used as a criterion for the prediction of curve progression in patients with scoliosis. The other clearly identifiable parameters during gait are thoracic and thoracolumbar spine hallmarks. The comparison of radiographically obtained Cobb-angles with motion capture data showed that MoCap angular values from the skin markers were somewhat lower than the radiographic indices. Sagittal thoracic ROM which depends on the Cobb-angle was increased in all patients. However, in the course of the physiotherapy and bracing program this parameter significantly decreased. The differences in range of motion between the initial and final assessment results, were most likely explained by an increased flexion extension movement during gait associated with lateral flexion of the scoliotic thoracic spine. In the registration process, the curvature angles in thoracolumbar and lumbar segments were based on the coordinate system increasing the possibility of projection error and were one of the limitations in our study. Another major limitation in this study was the small number of participants.

A reliable anterior hallmark or a reference point, essential for the construction of a dynamic coordinate system, was missing for this part of the spine. The lack of data on reliability of between-session results limits the possibility to re-assess the spinal curvature angular parameters on a test-retest basis, applied routinely to report progression of the disease or to assess treatment efficacy. The accuracy of marker placement was very high and data on the consistency of repeated use of markers confirmed the sufficient sensitivity of the method. Collected data from the assessment of spinal angular parameters during gait may form the background to develop a standard clinical examination procedure for patients with scoliosis. Together with muscle thickness and volume measurements, the kinematic data constitute a reliable model for the assessment of physical rehabilitation outcomes in patients with idiopathic scoliosis.

Our study was an attempt to look closely at the biomechanical pattern of the spine changes during the gait and myometric data in patients with scoliosis. The myometric data supplemented and supported our understanding of changes in spinal biomechanics in the course of physical therapy intervention. The analysis of spinal curvature revealed marked differences in angular values registered in sagittal and frontal planes, combined with changed pattern of sagittal movements of the thoracic spine. This confirmed that the dynamic changes of the scoliotic spine could be assessed by the optical non-invasive methods, which might be incorporated into the protocol of clinical gait analysis. The biomechanical and myometric data can make a solid basis for developing simulation models used for the dynamic assessment of the scoliotic spine fluctuations during gait and assessment of outcomes in patients with scoliosis.

Conflict of interest: Authors have nothing to declare.

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