Kütahya Dumlupınar University
Institute of Graduate Studies

Journal of Scientific Reports-A
E-ISSN: 2687-6167
Number 54, September 2023

RESEARCH ARTICLE

ANALYSIS AND CLINICAL EVALUATION OF MUSCLE DYNAMICS IN ADOLESCENTS WITH SAGITTAL PLANE DEFORMITY

Kadir GÖK[1], Ela Naz GÖK[2]*, Kadriye TOMBAK[3], Nehir SAMANCI KARAMAN[4], Ömer Halil ÇOLAK[5]

[1]Akdeniz University, Faculty of Engineering, Department of Electrical and Electronics Engineering, Antalya, kadirgok@akdeniz.edu.tr, ORCID: 0000-0003-3386-1512
[2]Akdeniz University, Faculty of Engineering, Department of Electrical and Electronics Engineering, Antalya, elanazdoger@gmail.com, ORCID: 0009-0000-5626-4652
[3]Akdeniz University, Health Services Vocational School, Department of Physical Therapy and Rehabilitation, Antalya, kadriyetombak@akdeniz.edu.tr, ORCID: 0000-0002-9574-7443
[4]Akdeniz University, Faculty of Medicine, Department of Internal Medicine, Department of Physical Medicine and Rehabilitation, Antalya, nehirsamanci@akdeniz.edu.tr, ORCID: 0000-0002-0110-1650
[5]Akdeniz University, Faculty of Engineering, Department of Electrical and Electronics Engineering, Antalya, omercol@akdeniz.edu.tr, ORCID: 0000-0003-0293-3931

Receive Date: 12.05.2023 *Accepted Date: 08.06.2023*

ABSTRACT

Sagittal plane deformity can be defined as a deviation from the normal curvature of the spine in the sagittal plane. This deformity can distort the natural shape of the spine and cause posture problems. In recent years, effects such as reduced activity in daily life, increased time spent in front of computers and mobile phones, and inactivity during the recent pandemic have also led to a significant increase in sagittal plane deformity. In this study, 16 healthy adolescents and 16 adolescents with sagittal plane deformity participated. Surface EMG (sEMG) recordings were obtained from thoracal kyphosis subjects and lumbar lordosis subjects, commonly seen in patients with sagittal plane deformity (SPD), and from healthy subjects. After filtering the raw sEMG data, wavelet packet transform analysis was performed. The energy values of the wavelet packets corresponding to the low and high frequency components have been calculated. These energy values were statistically analysed using the Mann-Whitney U test to determine muscle differences between SPD subjects and healthy subjects. This statistical analysis identified the channels with significant differences between SPD subjects and healthy subjects. Channels with a statistical significance level of $p<0.05$ were included. When the muscle activation of these channels was compared, higher activity was found in SPD subjects, while in some movements activation was found in different channels in SPD subjects and healthy subjects. SPD subjects showed more muscle activity than healthy subjects and spent more energy to increase the quality of movements and to perform them with the correct muscle dynamics. It has been observed that SPD subjects develop compensations from different muscle regions in order to perform movements correctly due to postural changes. In healthy subjects, it was observed that movements were completed in accordance with the kinematics of the movement and that maximum movement quality was observed with less energy.

Keywords: *surface electromyography, wavelet packet transform, lumbar lordosis, thoracal kyphosis, adolescence, bioelectric signals*

1. INTRODUCTION

There are natural anatomical curvatures in the spine that occur congenitally and with the transition to bipedal posture [1]. These natural curvatures are located at different angles and directions in the sagittal plane. Outward curvature of the spine in the thoracic region is called kyphosis, while inward curvature in the cervical and lumbar regions is called lordosis. For some reasons, abnormalities of kyphosis and lordosis (increased or decreased curvature) can occur. This can lead to a variety of postural problems, physical pain, breathing difficulties, reduced quality of life and sometimes medical intervention. In a study, the normal range for radiological measurement of thoracic kyphosis was reported as 20° to 50° degrees using radiographic images from 121 healthy children in a standard position [2]. In another study, lumbar lordotic angle (LSA) and lumbosacral angle (LSA) values were calculated from radiographs of 140 subjects of different ages. Normal LLA values were found between 20.9° and 68° degrees, and normal LSA values were found between 15° and 51° degrees [3]. It has been reported that when the thoracic kyphosis angle exceeds the normal value, musculoskeletal complaints such as postural affections, shoulder and cervical pain can affect all age groups [4], [5]. In the measurement of thoracic kyphosis, it has been stated that the evaluation of the muscular system as well as the skeletal system is an important aspect [6]. Most cases of adolescent idiopathic scoliosis (AIS) with coronal plane abnormalities are also associated with sagittal plane problems [7], [8]. In another study, it was mentioned that the correct assessment of sagittal alignment in AIS cases cannot be neglected due to the effect of both plane movements on each other. This study also reported that angular progression in AIS cases may be influenced by sagittal balance [9], [10]. Although it is difficult to restore the normal value of the kyphosis angle in subjects with only sagittal plane problems, it has been mentioned that the sagittal plane disorder, kyphosis, should be corrected [11].

There are studies that show that the functional and medical importance of lumbar lordosis has been recognised. [12], [13]. The natural curvature of the lumbar lordosis plays an important role in maintaining sagittal balance. The need to evaluate the effect of increasing changes in lumbar lordosis curvature on muscle dynamics and mechanics has been mentioned [14]. In one study, an 8-week exercise programme was designed for female students aged 19-22 years with lumbar lordosis. This study, designed to identify, train, prevent and improve unhealthy habits in corrective exercise and daily life, found no increase in lower extremity flexor muscle flexibility, a significant decrease in the lordosis curve, and an increase in abdominal muscle strength and endurance [15]. In the literature, it has been observed that the comprehensive muscle dynamics of thoracic kyphosis and lumbar lordosis have not been evaluated much and the follow-up and treatment of the cases is mostly focused on strengthening the muscle strength. In this process, it was observed that radiological methods were used as the gold standard. However, this gold standard cannot be used practically in clinics and is not preferred due to the negative secondary effects of radiation [16].

Surface EMG (sEMG) allows the assessment of muscle functional status by measuring bioelectrical signals from muscles using a non-invasive electrode placed on the muscle. sEMG signals are used in a variety of applications including assessment of muscle and nerve health, rehabilitation, biomechanics, sports performance, prosthetic control and ergonomics [17], [18], [19], [20], [21], [22]. Methods for extracting features from sEMG signals are generally divided into time domain features and frequency domain features. Commonly used time domain analyses include root mean square [23], variance [24], mean absolute value [25], zero crossing [26] and waveform length. In frequency domain analysis, after obtaining the frequency spectrum, the magnitude of the signal is evaluated using parameters such as power spectral density, mean frequency and median frequency [27]. The sEMG signal is an unstable, i.e. non-stationary, bioelectrical signal with different frequency components at different times [28]. Therefore, analysis of the sEMG signal in the time-frequency domain allows detailed examination of time- and frequency-dependent changes. Among the time-frequency analysis methods, Fast Fourier Transform [29] and Short-Time Fourier Transform [30] require the signal to be stable in order to effectively analyse the signal. However, the Wavelet transform [31], by multiplying the signal by more than one wavelet function, allows the decomposition of the components of the signal in different frequency bands. Wavelet packet transform is a widely used technique in many fields such as signal processing and data analysis. It is a method used to analyse the signal in frequency space. Wavelet Packet Transform has a significant impact on the processing of electromyography (EMG) signals. It is used to analyse the frequency content of the EMG signal and to determine the time-variance characteristics of the signal [32]. In this way, the frequency content of the EMG signal is better understood and the study of changes in muscle activity becomes more sensitive.

In this study, sEMG recordings were made to determine the multi-channel functional muscle dynamics of healthy subjects' spines and sagittal plane deformity (SPD) subjects in adolescence. The hypothesis of the study is that as the natural curvature of the spine increases in the sagittal plane, muscle dynamics will also change due to anatomical changes in the associated muscles. At the same time, although radiological measurement techniques are used in diagnosis and follow-up, studies on comprehensive electrophysiological signal-based assessment of muscle function are currently limited. In this context, adolescents with thoracal kyphosis and lumbar lordosis, which are common patient profiles of SPD subjects, were included in the study. A total of 32 subjects were recorded at a sampling frequency of 2000 Hz during 15 movements with electrodes placed in 18 muscle regions for 4 repetitions. Stable recordings of the subjects were completed using the prepared video and voice command interface. Raw sEMG data were filtered and analysed using wavelet packet transform analysis. Statistical analyses were performed on the analysis data.

2. MATERIALS AND METHODS

2.1. Ethics

This study contains human research data. Therefore, the ethics committee approval to confirm the ethical appropriateness of the study was determined as Akdeniz University Clinical Research Ethics Committee Approval number 70904504/271. All data used in our study were collected with the prior informed consent of the participants. Participants and their legal parents were fully informed about the aims of the study and their consent to participate as participants was obtained.

2.2. Subjects Information

In the study, sEMG recordings were obtained from 16 healthy participants in adolescence and 16 SPD subjects in adolescence. Since the data of healthy subjects were compared with those of SPD subjects, it was ensured that the age, weight, height and spinal curvature levels of the subjects were homogenous. For the healthy subjects group, 8 male and 8 female adolescents were enrolled. Thoracal kyphosis and lumbar lordosis were diagnosed by a specialist physician in 8 and 8 adolescents with SPD, respectively.

In our study, SPD subjects with major pathology of thoracal kyphosis or major pathology of lumbar lordosis were included in the study. When the demographic characteristics of the groups were compared, there was no statistically significant difference between the groups ($p>0.05$). The results of this evaluation, statistically analysed using the Mann-Whitney U test, are presented in Table 1. This result shows that the groups are similar in terms of the distribution of demographic and physical characteristics.

Table 1. Descriptive characteristics of the groups (Man Whitney U test, n; Sample Size, X; Mean, SD; Standard Deviation; p; p Value).

	Healty Subjects (n=16)		**SPD Subjects (n=16)**		
	X	**SD**	**X**	**SD**	**p**
Age (years)	13.81	1.60	14.75	2.62	0.323
Height (cm)	1.63	0.10	1.62	0.11	0.752
Body mass (kg)	54.56	8.62	51.38	13.30	0.224

2.3. Inclusion and Exclusion Criteria in Research

The inclusion criteria for SPD subjects were that they had been diagnosed by a specialist as having a sagittal plane spinal deformity, had no congenital problems, and had been accepted into the appropriate physiotherapy and rehabilitation programme. SPD subjects with major pathology of thoracal kyphosis or major pathology of lumbar lordosis were selected. Inclusion criteria for healthy subjects were the absence of spinal deformity and the absence of any disease that would interfere with the study. Adolescents were included in the study. Exclusion criteria were that patients with other primary or secondary diagnoses or diseases such as neuromuscular, congenital or syndromic (connective tissue disorders) were not included in the study. Patients who could not participate 100% or who refused to participate during the study were not included in the analysis phase.

2.4. Surface Electromyography (sEMG) Recording

sEMG recordings were obtained using PowerLab 35/8 and PowerLab 35/16 units from ADInstruments. Bipolar 9 mm diameter electrodes were placed on the muscles to receive EMG data. sEMG data were recorded simultaneously from 18 muscle sites at a sampling frequency of 2000 Hz during movement. The locations of these channels are shown in which muscle region on the model in Figure 1.

JSR A
Journal of Scientific Reports

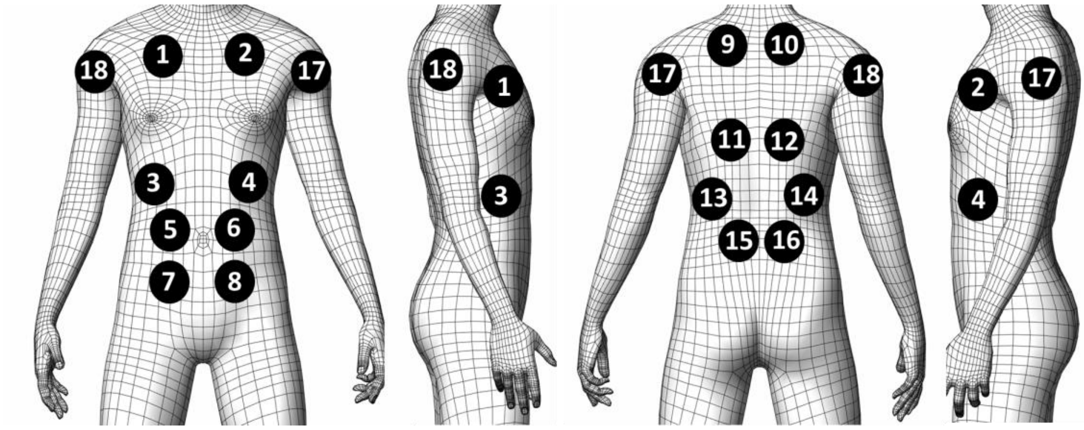

Figure 1. sEMG Recording Channels.

Channels 1,2,3,4,4,5,6,7,8 were used on the front of the body and channels 10,11,12,13,14,15,16 were used on the back of the body. Channel 17 was used on the left shoulder and channel 18 on the right shoulder. When viewed from the front of the body, odd numbered channels were placed on the left side of the body and even numbered channels were placed on the right side of the body. When viewed from the rear of the body, the odd numbered channels are attached to the left side of the body and the even numbered channels are attached to the right side of the body. Channels 1 and 2 are attached to the pectoralis major muscle (pectoral muscle region), channels 3 and 4 to the oblique muscle (lateral abdominal muscle region), channels 5, 6, 7 and 8 to the rectus abdominis muscle (abdominal muscle region), channels 9, 10, 11 and 12 to the trapezius muscle (upper back muscle region), channels 13,14,15 and 16 to the latissimus dorsi muscle (waist muscle region) and channels 17 and 18 to the deltoid muscle.

The movements performed in the recordings were selected accordingly, as it was planned that the movements performed in the recordings would provide data for the biomechanical model to be built in the future. A total of 15 movements were performed, including right shoulder flexion, left shoulder flexion, right shoulder extension, left shoulder extension, right shoulder abduction, left shoulder abduction, right shoulder adduction, left shoulder adduction, right shoulder horizontal, left shoulder horizontal, trunk flexion, right trunk flexion, left trunk flexion, scapula protraction, scapula retraction. Each movement was performed for 4 repetitions.

In order to make the movements of the recorded subjects as same as possible, an interface application was developed. In this interface, projected on the screen, the recorded subject was enabled to follow the muscle-rest commands. In this interface, the person performing the movement was visually and audibly monitored by the loudspeaker. Duration of the movement sequence: Starting with 4 seconds in the free state to prepare the movement, 4 repetitions were made in the form of 3 seconds in the free state for 3 seconds to be in the state of performing the movement for 3 seconds.

2.5. Surface Electromyography (sEMG) Analysis

In our study, EMG signals obtained from subjects were analysed by developing algorithms in Matlab using signal processing methods. A 50 Hz notch filter and a 5 degree Butterworth 10-500 Hz bandpass filter were applied to remove the mains hum of the electromyography responses and to work in the significant frequency domain. From the filtered data of each channel, 4 repetitions at the moment of contraction were selected to be processed separately. As the start of the recording was synchronised with the movement notification interface, this selection was made with the time of the start of the recording, the contraction and relaxation times of the movement. The data was then analysed using Wavelet Packet Transform (WPT). The method of analysis is shown in Figure 2.

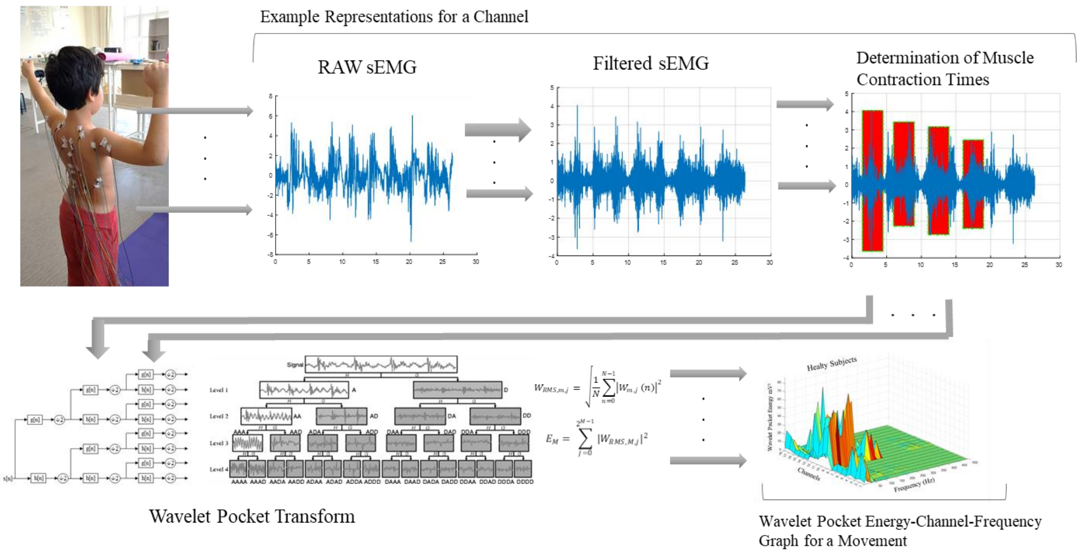

Figure 2. sEMG Data Analysis Scheme.

The wavelet transform method is a mathematical method used to analyse the signal at different scales and times [33]. It is based on the principles of wavelet analysis and helps to decompose the time and frequency components of data [34]. Daubechies level-7 was used for scaling. Daubechies wavelet filters are computationally efficient and effective, capable of capturing low and high frequency components in a consistent manner, supporting symmetrical and compact manner [35]. In the wavelet transform, high-pass filters are related to wavelet functions, while low-pass filters are related to scaling functions [32]. The following equations define the expansion equation for the scaling function $\phi(t)$ and the wavelet equation for the wavelet function $\psi(t)$ using the filter coefficients:

$$\phi(t) = \sqrt{2}\, \sum_{k=0}^{N} g(k)\phi(2t-k) \tag{1}$$

$$\psi(t) = \sqrt{2}\, \sum_{k=0}^{N} h(k)\phi(2t-k) \tag{2}$$

JSR A
Journal of Scientific Reports

Gök, et al., Journal of Scientific Reports-A, Number 54, 42-61, September 2023

$$h(k) = (-1)^k g(N-k) \quad (3)$$

$g(k)$ in Eq. 1 are the low pass filter coefficients and $h(k)$ in Eq. 2 are the high pass filter coefficients. The relationship between the low pass filter coefficients and the high pass filter coefficients is shown in Eq. 3 [32]. Here N is the total number of filter coefficients. For WPT, the low pass filter $W_{2J+1}(t)$ and the high pass filter $W_{2J}(t)$ can be defined as follows [33,34].

$$W_{2J+1}(t) = \sqrt{2}\sum_{k=0}^{2j-1} g(k)\, W_J(2t-k) \quad (4)$$

$$W_{2J}(t) = \sqrt{2}\sum_{k=0}^{2j-1} h(k)\, W_J(2t-k) \quad (5)$$

For the WPT, we denote the scaling function by $W_0(t)$, the wavelet function by $W_1(t)$ and the node index j at each level. Low-pass filters are defined as $W_{2J+1}(t)$ and high-pass filters as $W_{2J}(t)$, while the wavelet function $W_J(t)$, a generalisation of the coupling between packets with three indices, can be calculated by Eq. 6 [35].

$$W_{m,j,n}(t) = 2^{-m/2}\; W_j\,(2^{-m}t - n) \quad (6)$$

The level index $j, j \in N$, the time shift parameter n and the scaling parameter m are defined as $(m,n) \in Z^2$. For each node, the root mean square (rms) value in the wavelet packet transform is calculated as in Eq. (7) [36].

$$W_{RMS,m,j} = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1}\left|W_{m,j}\,(n)\right|^2} \quad (7)$$

$W_{m,j,n}(t)$ is the square root of the sum of squares of $W_{mj}(n)$ divided by the length of $W_{mj}(n)$ calculated by the reconstruction. After calculating the RMS value for each node in the WPT, the total wavelet packet energy (WPE) is found. It is obtained by taking the sum of the absolute squares of all RMS values from the initial node index to node $2^M - 1$ [36].

$$E_M = \sum_{j=0}^{2^{M-1}} |W_{RMS,M,j}|^2 \quad (8)$$

$W_{RMS,M,j}$ is the RMS value of each of the last level nodes at M levels of the WPT, and E_M is the total signal energy obtained as a result of the M level transformation. In order to identify the muscles that contract during the movements and to determine whether they produce significant values, the energy components obtained were summed for each channel and analysed statistically.

The sample size of the study was analysed using G*Power software (Universitat Kiel, Germany). As a result of the sample size analysis, it was determined that a minimum of 16 subjects should be included in each group. In the study, it was aimed to reach an effect size of 0.92 and a power level of 0.80 [37]. The Mann-Whitney U test was used to determine the differences in characteristics between healthy and SPD subjects. The level of statistical significance was accepted as $p<0.05$. Below this value, statistically significant differences were found between healthy subjects and SPD subjects in terms of the channels activated by movement. In the conclusion section, the results of the statistical analyses of the movements with significant differences between healthy subjects and SPD subjects are presented.

3. RESULTS

Upon completion of the recording stages, signal processing techniques were applied. Raw sEMG data were filtered. Wavelet packet energy (WPE) values of muscle activations were obtained from these filtered sEMG data using the WPT method. The WPE value of a muscle was compared between healthy subjects and SPD subjects. For muscles with high WPE values during movement, we have information about the number and amount of contracted muscle fibres. In addition to this, it is expected that the muscle with high activity will cause more energy requirement and energy consumption [38]. WPE values were calculated at 64 nodes. Three-dimensional graphs were generated using the WPE values, frequency and channel axis information corresponding to each node in the low and high frequency ranges. For statistical analysis, the WPE values of the channels at 64 nodes were summed and statistical values were extracted.

Table 2. Statistical analysis of trunk flexion movement results with significant differences between healthy subjects and SPD subjects. (Mann-Whitney U test, n; Sample Size, X; Mean, SD; Standard Deviation; p; p Value).

Movement	Channels	Healthy Subjects (n=16)		Sagittal Plane Deformity Subjects (n=16)		
		X	SD	X	SD	p
Trunk Flexion	Channel 5	18	0,70	122	15,20	0.001
	Channel 7	99	16,80	185	17,70	0.046
	Channel 8	25	3,30	88	13,30	0.003
	Channel 12	605	71,40	177	10,10	0.004
	Channel 15	182	10,80	411	59,80	0.036
	Channel 17	583	47,10	1714	214,20	0.014

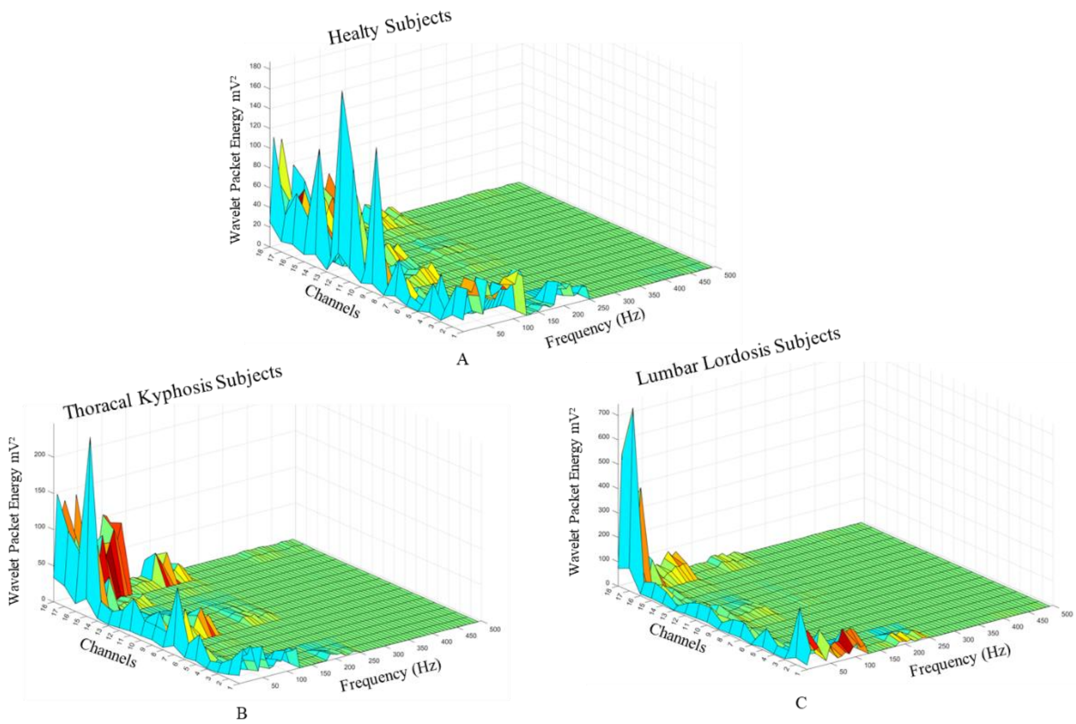

Figure 3. Trunk flexion movement WPE results (3A. Healty Subjects, 3B. Thoracal Kyphosis Subjects, 3C. Lumbar Lordosis Subjects).

For the trunk flexion movement, Figure 3 shows the 3D plots of the WPE values corresponding to each node in the low and high frequency ranges with frequency and channel axis. Figure 3A shows the 3D plots of the analysis results for the trunk flexion motion of healthy subjects, Figure 3B for thoracal kyphosis subjects and Figure 3C for lumbar lordosis subjects. Table 2 shows the WPE mean, standard deviation and p-values of the statistical analysis results between healthy subjects and SPD subjects. The 3D plots in Figure 3 were evaluated in the light of the statistically significant difference channels in Table 2. In Table 2, the abdominal (5th channel p-value 0.001, 7th channel p-value 0.046 and 8th channel p-value 0.003), upper back (12th channel p-value 0.004), waist (15th channel p-value 0.036) and deltoid (17th channel p-value 0.014) muscle regions were found to have statistically significant differences between SPD subjects and healthy subjects. Figure 3A shows that WPE values from healthy subjects show activity up to the 235,375 Hz range. In Figure 3B, WPE values from thoracal kyphosis subjects showed activity up to the 251 Hz band. In Figure 3C, WPE values from lumbar lordosis subjects showed activity up to the 243,188 Hz band. When analysing the channels with a statistically significant difference, activity was detected in the upper back muscle region in healthy subjects. In thoracal kyphosis subjects, muscle activity was found in the waist muscle region and deltoid muscle regions. In lumbar lordosis subjects, activity was found in the deltoid muscle.

JSR A
Journal of Scientific Reports

Statistically significant differences were found in the muscle dynamics of healthy subjects and SPD subjects in the trunk flexion movement.

Table 3. Statistical analysis of scapular retraction movement results with significant differences between healthy subjects and SPD subjects. (Mann-Whitney U test, n; Sample Size, X; Mean, SD; Standard Deviation; p; p Value).

Movement	**Channels**	**Healthy Subjects (n=16)**		**Sagittal Plane Deformity Subjects (n=16)**		
		X	**SD**	**X**	**SD**	**p**
Scapular Retraction	Channel 1	35	3.2	77	12.3	0.029
	Channel 6	23	1.3	12	0.9	0.003
	Channel 9	1050	89.6	1655	237.4	0.034
	Channel 10	738	68.0	1067	112.8	0.042
	Channel 11	248	21.3	1443	167.9	0.001
	Channel 12	800	96.1	1445	152.8	0.040
	Channel 14	32	5.1	54	4.5	0.044
	Channel 15	19	1.4	72	8.9	0.018

JSR A
Journal of Scientific Reports

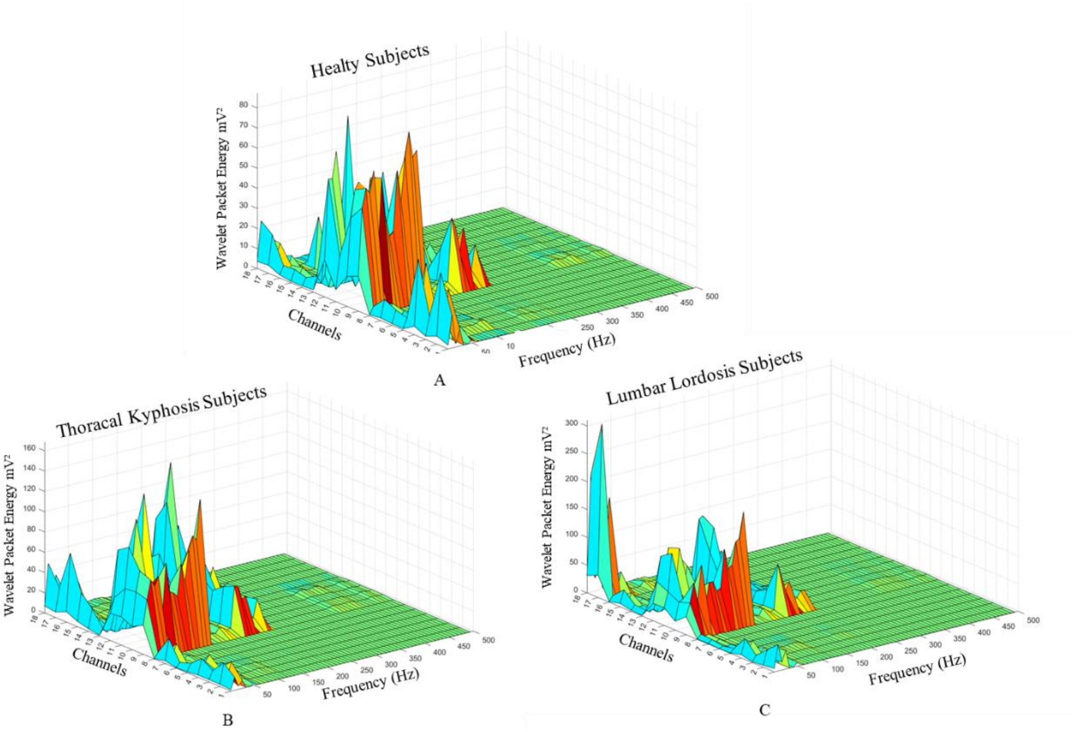

Figure 4. Scapular retraction movement WPE results (4A. Healty Subjects, 4B. Thoracal Kyphosis Subjects, 4C. Lumbar Lordosis Subjects).

For the scapular retraction movement, Figure 4 shows the 3D plots of the WPE values corresponding to each node in the low and high frequency ranges with frequency and channel axis. Figure 4A shows the 3D plot of the analysis results for the scapular retraction movement of healthy subjects, Figure 4B shows the 3D plot for thoracal kyphosis subjects and Figure 4C shows the 3D plot for lumbar lordosis subjects. The WPE mean, standard deviation and p-values of the results of the statistical analyses between healthy subjects and SPD subjects are shown in Table 3. The 3D plots in Figure 4 were evaluated in the light of the statistically significant difference channels in Table 3. When the muscle regions with statistically significant differences between SPD subjects and healthy subjects were analysed in Table 3, it was found that there were statistically significant differences in the pectoral muscle region (1st channel p value 0.029), upper back muscle region (9th channel p value 0.034, 10th channel p value 0.042, 11th channel p value 0.001 and 12th channel p value 0.040) and waist muscle region (14th channel p value 0.044 and 15th channel p value 0.018). Figure 4A shows that the WPE values of healthy subjects show activity up to the 243.88 Hz band. In Figure 4B, WPE values from thoracal kyphosis subjects showed activity up to the 227.562 Hz band. In Figure 4C, WPE values from lumbar lordosis subjects showed activity up to the 243.188 Hz band. When analysing the channels with statistically significant difference, activity was detected in the upper back muscle region in healthy subjects and in SPD subjects. However, the WPE values were more dominant in SPD subjects than in healthy subjects. A statistically significant difference was found in the upper back muscles of SPD subjects during the scapular retraction movement, and it was found that SPD subjects performed the movement using more energy.

Table 4. Statistical analyses of right shoulder flexion movement results with significant differences between healthy subjects and SPD subjects. (Mann-Whitney U test, n; Sample Size, X; Mean, SD; Standard Deviation; p; p Value).

Movements	**Channels**	**Healthy Subjects (n=16)**		**Sagittal Plane Deformity Subjects (n=16)**		
		X	**SD**	**X**	**SD**	**p**
Right Shoulder Flexion	Channel 1	152	16.2	307	26.9	0.019
	Channel 9	20	0.6	83	7.8	0.002
	Channel 10	977	115.5	1759	139.6	0.038
	Channel 12	1228	317.1	1860	297.7	0.038
	Channel 15	21	1.6	116	14.7	0.000
	Channel 17	1306	123.3	635	167.7	0.029

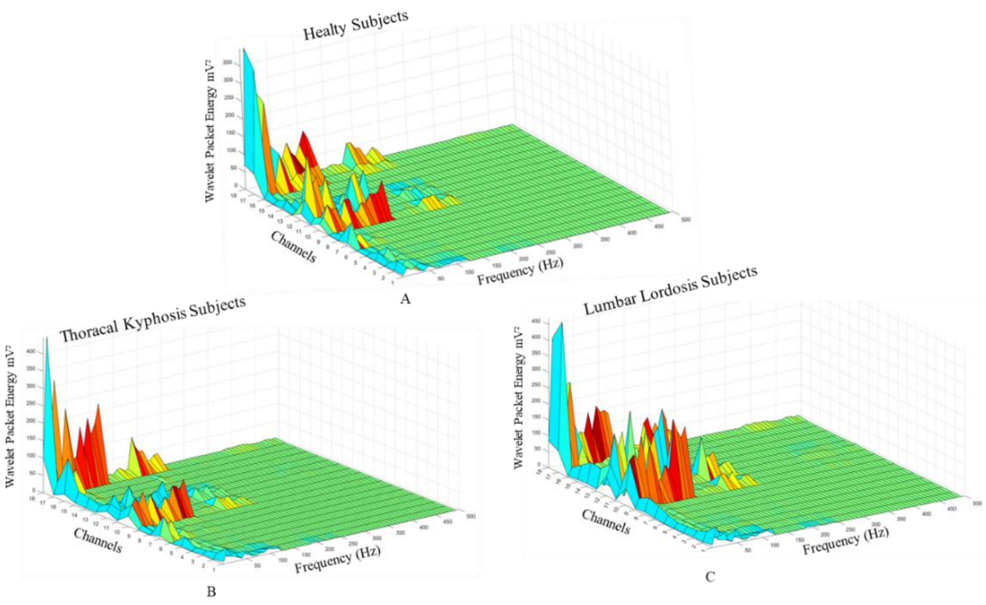

Figure 5. Right shoulder flexion WPE results (5A. Healty Subjects, 5B. Thoracal Kyphosis Subjects, 5C. Lumbar Lordosis Subjects).

JSR A
Journal of Scientific Reports

Gök, et al., Journal of Scientific Reports-A, Number 54, 42-61, September 2023

For the right shoulder flexion movement, Figure 5 shows the 3D plots of the WPE values corresponding to each node in the low and high frequency ranges with frequency and channel axis. Figure 5A shows the 3D plot of the analysis results for the right shoulder flexion movement of healthy subjects, Figure 5B for thoracal kyphosis subjects and Figure 5C for lumbar lordosis subjects. The mean WPE, standard deviation and p-values of the statistical analyses between healthy subjects and SPD subjects are shown in Table 4. The 3D plots in Figure 5 were evaluated using the channels with statistically significant differences in Table 4. When the muscle regions with statistically significant differences between SPD subjects and healthy subjects were analysed in Table 4, they were found in the pectoral muscle region (1st channel p-value 0.019), upper back muscle region (9th channel p-value 0.002, 10th channel p-value 0.038 and 12th channel p-value 0.038), waist muscle region (15th channel p-value 0.000) and deltoid muscle (17th channel p-value 0.029). Figure 5A shows that WPE values from healthy subjects show activity up to the 235,375 Hz band. In Figure 5B, WPE values from thoracal kyphosis subjects showed activity up to the 243,118 Hz band. In Figure 5C, WPE values in lumbar lordosis subjects showed activity up to the 251 Hz band. When the channels with statistically significant difference were examined, activity was detected in the right upper back and deltoid regions in healthy subjects, in the right upper back and deltoid regions in thoracal kyphosis subjects, and in the right upper back and deltoid regions in lumbar lordosis subjects. Although the muscle dynamic positions were present in the same muscle regions, the WPE value was higher in SPD subjects. It was found that SPD subjects performed the movement by using more energy.

Table 5. Statistical analysis of trunk left flexion movement results with significant differences between healthy subjects and SPD subjects. (Mann-Whitney U test, n; Sample Size, X; Mean, SD; Standard Deviation; p; p Value).

Movements	**Channels**	**Healthy Subjects (n=16)**		**Sagittal Plane Deformity Subjects (n=16)**		
		X	**SD**	**X**	**SD**	**p**
Trunk Left Flexion	Channel 4	272	39.6	64	5.8	0.018
	Channel 7	19	2.3	82	9.9	0.004

JSR A
Journal of Scientific Reports

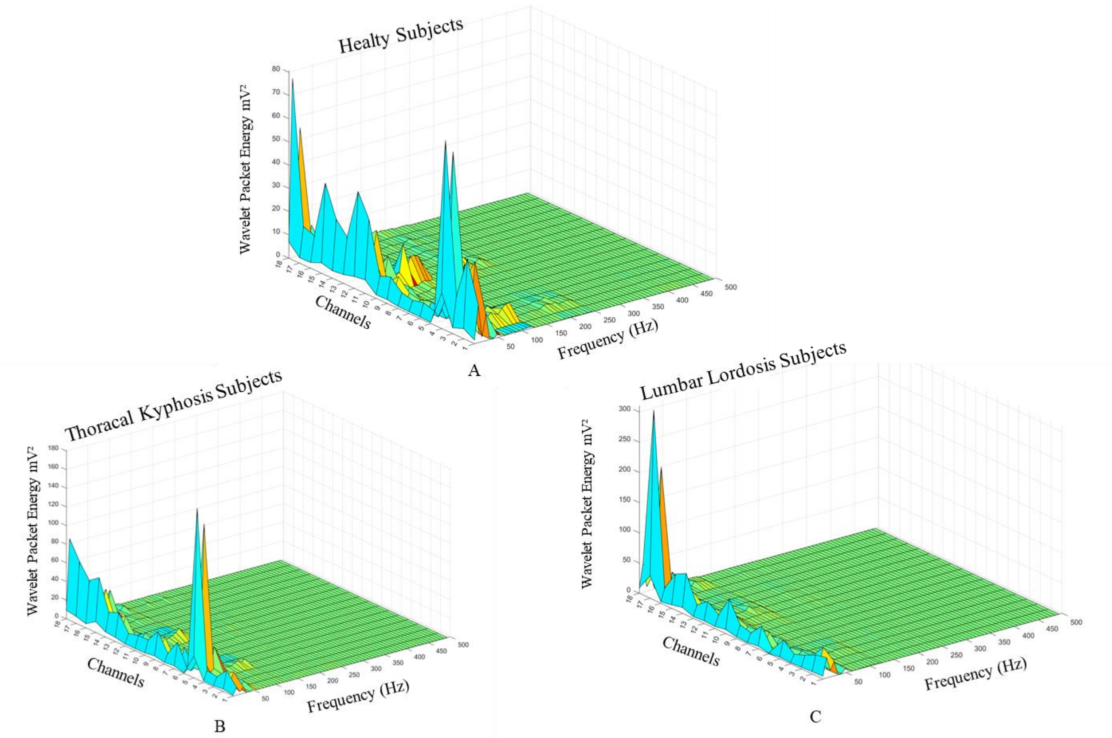

Figure 6. Left lateral flexion movement WPE results (6A. Healty Subjects, 6B. Thoracal Kyphosis Subjects, 6C. Lumbar Lordosis Subjects).

For left lateral flexion, Figure 6 shows the 3D plots of the WPE values corresponding to each node in the low and high frequency ranges with frequency and channel axis. Figure 6A shows the 3D plot of the analysis results for the left lateral flexion motion for healthy subjects, Figure 6B for thoracal kyphosis subjects and Figure 6C for lumbar lordosis subjects. The mean WPE, standard deviation and p-values of the statistical analyses between healthy subjects and SPD subjects are shown in Table 5. The 3D plots in Figure 6 were evaluated in the light of the channels with statistically significant differences in Table 5. When the muscle regions with statistically significant differences between SPD subjects and healthy subjects were analysed in Table 5, the lateral abdominal muscle region (4th channel p-value 0.018) and the abdominal muscle region (7th channel p-value 0.004) were found. Figure 6A shows that the WPE values of healthy subjects show activity up to the 188.5 Hz band. In Figure 6B, WPE values from thoracal kyphosis subjects showed activity up to the 110.375 Hz band. In Figure 6C, WPE values from lumbar lordosis subjects showed activity up to the 94.75 Hz band. When the channels with statistically significant difference were analysed, activity was detected in the lateral abdominal muscle region and in the abdominal muscle region in healthy subjects. In thoracal kyphosis subjects, activity was detected in the lateral muscle region, while in lumbar lordosis subjects, muscle activity could not be detected in muscle regions with a statistically significant difference.

JSR A
Journal of Scientific Reports

4. DISCUSSIONS

In this study, muscle dynamics of healthy subjects, subjects with thoracal kyphosis and lumbar lordosis were determined using sEMG data obtained from 18 channels during 15 movements. The results of the sEMG analysis and the statistical analysis of the data are presented in the results section.

When analysing the channels with a statistically significant difference in the trunk flexion movement, activity was detected in the upper back muscle region in healthy subjects, in the waist muscle region and deltoid muscle in thoracal kyphosis subjects and in the deltoid muscle in lumbar lordosis subjects. In the trunk flexion movement, the back muscles contract and try to stabilise the movement, while healthy subjects tilt their trunk forward. They complete the movement according to the kinematics of the movement. However, in SPD subjects, muscle activation is impaired due to the increased sagittal plane deformity, so they try to complete the movement with the support of the waist or shoulder muscle region to compensate. If we explain the compensatory mechanism [39], SPD subjects complete the movement with other muscle groups and supports instead of the upper back muscle region. In other words, it was observed that during trunk flexion movement, other muscle groups were used instead of extensor (back) muscle groups. The clinical significance of this is that by not being able to provide the correct muscle contraction dynamics, SPD subjects are at risk of increasing lordosis or kyphosis curvatures, requiring more energy than necessary, resulting in fatigue and musculoskeletal problems. It has been reported in the literature that the natural curvature of the spine in the sagittal plane is responsible for postural balance [11,12], and that musculoskeletal complaints such as postural affection, shoulder and cervical pain may occur when the natural curvature increases [3,4]. As a result of our study, the spatial variation of muscle dynamics in SPD subjects supports the findings of disease progression with the literature.

In the scapular retraction movement, when analysing the channels with a statistically significant difference, activity was detected in the upper back muscle region in healthy subjects and SPD subjects. However, the WPE values of SPD subjects were more dominant than healthy subjects. A statistically significant difference was found in the upper back muscles of SPD subjects in the scapular retraction movement. It was found that SPD subjects performed the movement with more energy. Particularly in thoracal kyphosis subjects, as the curvature of the thoracic region increases, the muscle activation required for postural control during this movement is more intense. For this reason, rehabilitation programmes are used to help these subjects use energy correctly and economically. Thoracal kyphosis subjects expend more energy than healthy subjects to increase the quality of movement and to perform it with the right combination. As in healthy subjects, maximum movement quality is aimed for with less energy. In addition, because the posterior group muscles (back muscles) are already in an abnormal muscle position in thoracal kyphosis subjects, they perform the movement with more energy in the scapular retraction movement. It has been suggested in the literature that musculoskeletal information for rehabilitation programmes applied to SPD subjects provides valuable information for the recovery process and that assessment of the musculoskeletal system together with the skeletal system is an important aspect of measuring thoracic kyphosis [5].

When analysing the statistical results of the right shoulder flexion movement, the muscle region with a statistically significant difference in the right shoulder flexion movement of SPD subjects and

JSR A
Journal of Scientific Reports

healthy subjects was found to be the right upper back muscle region and the deltoid muscle. A statistically significant difference was found in the right shoulder flexion movement between healthy subjects and SPD subjects. For the right shoulder flexion movement, it was found that SPD subjects performed more activity than healthy subjects. This is because SPD subjects use more energy to stand upright and show more muscle activity and faster muscle fatigue. When analysing the channels with a statistically significant difference for the left lateral flexion movement, activity was detected in the lateral abdominal muscle region and in the abdominal muscle region in healthy subjects. In thoracal kyphosis subjects, activity was detected in the lateral muscle region, whereas in lumbar lordosis subjects, muscle activity was not detected in the muscle regions with statistically significant difference, although there was no statistically significant difference in lumbar lordosis subjects. Therefore, subject-specific muscle activation gives meaning to the advantages and disadvantages of lordotic posture. It may also contribute to rehabilitation programmes.

SPD subjects with isolated thoracal kyphosis or lumbar lordosis are not commonly encountered in clinics. Therefore, subjects with major pathology of thoracal kyphosis and subjects with major pathology of lumbar lordosis were considered. Statistical analyses were compared between healthy subjects and SPD subjects. One reason for this is to increase the statistical significance and the other reason is to look for a significant difference between SPD subjects and healthy subjects. This difference was used to determine the channels with different muscle activation. The sample of our current group of healthy subjects and SPD subjects was limited in number. This information constitutes the limitations of our study.

5. CONCLUSION

In this study, a multi-channel sEMG-based study was developed to investigate the effect of sagittal plane spinal deformity on muscle dynamics in adolescents during movement. It was found that muscle activation values and positions of muscle dynamics changed in SPD subjects compared to healthy subjects. In our study, our statistical results served as a filter to evaluate the muscle regions with significant differences. Although there was muscle activity in the same muscle group in some movements, SPD subjects showed more intense activity, and the activity of different muscle groups in some movements statistically supported that SPD subjects activated different muscle regions. It was found that SPD subjects use a lot of energy while performing the movements and compensate from other muscle regions to perform the movement with high quality. As they cannot provide the correct muscle contraction dynamics, SPD subjects are at risk of further increasing lordosis or kyphosis curvatures. The clinical significance of the results will provide a new perspective in the diagnosis and treatment process. In the treatment process of changing muscle dynamics, we believe that the evaluation of muscle dynamics together with radiological images when creating rehabilitation programmes for SPD subjects in the treatment process can be followed more effectively in the healing process. At the same time, this study has provided a movement-based assessment of the dynamics of the muscles responsible for upright posture in healthy adolescents. We believe that this study will contribute to the literature as a useful resource for biomechanical modelling and kinematic analysis studies. For future studies, we believe that muscle dynamics should be evaluated in subjects with sagittal plane deformity in the presence of scoliosis, which is a 3D deformity of the spine.

ACKNOWLEDGEMENT

There is no conflict of interest with any person/institution in the prepared article.

REFERENCES

[1] Frost, B. A., S. Camarero-Espinosa and E. J. Foster (2019). "Materials for the spine: anatomy, problems, and solutions." Materials 12(2): 253.

[2] Boseker, E. H., J. H. Moe, R. B. Winter and S. E. Koop (2000). "Determination of “normal” thoracic kyphosis: a roentgenographic study of 121 “normal” children." Journal of Pediatric Orthopaedics 20(6): 796-798.

[3] Issahaku, S., E. Sackey, E. K. Tiburu and T. A. Sackey (2023). "Determination of the Lumbar Lordotic and Lumbosacral Angles in Normal Adults Ghanaian Population Using Radiologic Imaging Technique."

[4] Gray, J. C. and O. Grimsby (2012). "Interrelationship of the spine, rib cage, and shoulder." Physical therapy of the shoulder: 87-130.

[5] Barrett, E., K. McCreesh and J. Lewis (2014). "Reliability and validity of non-radiographic methods of thoracic kyphosis measurement: a systematic review." Manual therapy 19(1): 10-17.

[6] Chaise, F. O., C. T. Candotti, M. L. Torre, T. S. Furlanetto, P. Pelinson and J. F. Loss (2011). "Validation, repeatability and reproducibility of a noninvasive instrument for measuring thoracic and lumbar curvature of the spine in the sagittal plane." Brazilian Journal of Physical Therapy 15: 511-517.

[7] Perdriolle, R. and J. Vidal (1987). Morphology of scoliosis: three-dimensional evolution, SLACK Incorporated Thorofare, NJ. 10: 909-915.

[8] Fletcher, N. D., H. Jeffrey, M. Anna, R. Browne and D. J. Sucato (2012). "Residual thoracic hypokyphosis after posterior spinal fusion and instrumentation in adolescent idiopathic scoliosis: risk factors and clinical ramifications." Spine 37(3): 200-206.

[9] Parvaresh, K. C., E. J. Osborn, F. G. Reighard, J. Doan, T. P. Bastrom and P. O. Newton (2017). "Predicting 3D thoracic kyphosis using traditional 2D radiographic measurements in adolescent idiopathic scoliosis." Spine Deformity 5(3): 159-165.

[10] Hayashi, K., V. V. Upasani, J. B. Pawelek, C.-É. Aubin, H. Labelle, L. G. Lenke, R. Jackson and P. O. Newton (2009). "Three-dimensional analysis of thoracic apical sagittal alignment in adolescent idiopathic scoliosis." Spine 34(8): 792-797.

[11] Hwang, S. W., A. F. Samdani, M. Tantorski, P. Cahill, J. Nydick, A. Fine, R. R. Betz and M. D. Antonacci (2011). "Cervical sagittal plane decompensation after surgery for adolescent idiopathic scoliosis: an effect imparted by postoperative thoracic hypokyphosis." Journal of Neurosurgery: Spine 15(5): 491-496.

[12] Adams, M., D. McNally, H. Chinn and P. Dolan (1994). "The clinical biomechanics award paper 1993 posture and the compressive strength of the lumbar spine." Clinical Biomechanics 9(1): 5-14.

[13] Potvin, J., R. Norman and S. McGill (1991). "Reduction in anterior shear forces on the L4L5 disc by the lumbar musculature." Clinical Biomechanics 6(2): 88-96.

[14] McGill, S. M., R. L. Hughson and K. Parks (2000). "Changes in lumbar lordosis modify the role of the extensor muscles." Clinical biomechanics 15(10): 777-780.

[15] Ghorbani, L. and G. Ghasemi (2007). "Effects of eight weeks corrective exercises on lumbar lordosis." Journal of research in rehabilitation sciences 3(2).

[16] Pace, N., L. Ricci and S. Negrini (2013). "A comparison approach to explain risks related to X-ray imaging for scoliosis, 2012 SOSORT award winner." Scoliosis 8(1): 1-7.

[17] Farago, E., D. MacIsaac, M. Suk and A. D. Chan (2022). "A review of techniques for surface electromyography signal quality analysis." IEEE Reviews in Biomedical Engineering 16: 472-486.

[18] Turker, H. (2013). Electrodiagnosis in new frontiers of clinical research, BoD–Books on Demand.

[19] Gazzoni, M. (2010). "Multichannel surface electromyography in ergonomics: Potentialities and limits." Human Factors and Ergonomics in Manufacturing & Service Industries 20(4): 255-271.

[20] Taborri, J., J. Keogh, A. Kos, A. Santuz, A. Umek, C. Urbanczyk, E. van der Kruk and S. Rossi (2020). "Sport biomechanics applications using inertial, force, and EMG sensors: A literature overview." Applied bionics and biomechanics 20-20

[21] Li, G., O. W. Samuel, C. Lin, M. G. Asogbon, P. Fang and P. O. Idowu (2019). "Realizing efficient EMG-based prosthetic control strategy." Neural Interface: Frontiers and Applications: 149-166.

[22] Topçu, Ç., H. Uysal, Ö. Özkan, Ö. Özkan, Ö. Polat, M. Bedeloğlu, A. Akgül, E. N. Döğer, R. Sever and Ö. H. Çolak (2018). "Recovery of facial expressions using functional electrical stimulation after full-face transplantation." Journal of NeuroEngineering and Rehabilitation 15: 1

[23] Esposito, F., A. Veicsteinas, C. Orizio and D. Malgrati (1996). "Time and frequency domain analysis of electromyogram and sound myogram in the elderly." European journal of applied physiology and occupational physiology 73: 503-510.

[24] Altan, E., K. Pehlivan and E. Kaplanoğlu (2019). Comparison of EMG based finger motion classification algorithms. 2019 27th Signal Processing and Communications Applications Conference (SIU), IEEE.

[25] Ahamed, N. U., Z. Taha, M. Alqahtani, O. Altwijri, M. Rahman and A. Deboucha (2016). Age related differences in the surface EMG signals on adolescent's muscle during contraction. IOP Conference Series: Materials Science and Engineering, IOP Publishing.

[26] Junior, J. J. A. M., M. L. Freitas, H. V. Siqueira, A. E. Lazzaretti, S. F. Pichorim and S. L. Stevan Jr (2020). "Feature selection and dimensionality reduction: An extensive comparison in hand gesture classification by sEMG in eight channels armband approach." Biomedical Signal Processing and Control 59: 101920.

[27] Ferdjallah, M., J. J. Wertsch and R. Shaker (2000). "Spectral analysis of surface electromyography (EMG) of upper esophageal sphincter-opening muscles during head lift exercise." Journal of rehabilitation research and development 37(3): 335-340.

[28] Chowdhury, R. H., M. B. Reaz, M. A. B. M. Ali, A. A. Bakar, K. Chellappan and T. G. Chang (2013). "Surface electromyography signal processing and classification techniques." Sensors 13(9): 12431-12466.

[29] Camata, T. V., J. L. Dantas, T. Abrão, M. A. Brunetto, A. C. Moraes and L. R. Altimari (2010). Fourier and wavelet spectral analysis of EMG signals in supramaximal constant load dynamic exercise. 2010 Annual International Conference of the IEEE Engineering in Medicine and Biology, IEEE.

[30] Sparto, P. J., M. Parnianpour, E. A. Barria and J. M. Jagadeesh (2000). "Wavelet and short-time Fourier transform analysis of electromyography for detection of back muscle fatigue." IEEE Transactions on rehabilitation engineering 8(3): 433-436.

[31] Zhang, X., Y. Wang and R. P. Han (2010). Wavelet transform theory and its application in EMG signal processing. 2010 Seventh International Conference on Fuzzy Systems and Knowledge Discovery, IEEE.

[32] Strang, G. and T. Nguyen (1996). Wavelets and filter banks, SIAM.

[33] Rong, Y., D. Hao, X. Han, Y. Zhang, J. Zhang and Y. Zeng (2013). "Classification of surface EMGs using wavelet packet energy analysis and a genetic algorithm-based support vector machine." Neurophysiology 45: 39-48.

[34] Wallen, R. D. (2004). "The illustrated wavelet transform handbook." Biomedical Instrumentation & Technology 38(4): 298-298.

[35] Daubechies, I. (1992). Ten lectures on wavelets, SIAM.

[36] Englehart, K., B. Hudgin and P. A. Parker (2001). "A wavelet-based continuous classification scheme for multifunction myoelectric control." IEEE Transactions on Biomedical Engineering 48(3): 302-311.

[37] Tombak, K. (2021). Adölesan idiopatik skolyozda kontrollü schroth egzersiz ve ev programlarının gövde simetrisi, deformite algısı ve yaşam kalitesi üzerindeki etkilerinin karşılaştırılması (Doctoral dissertation), Eastern Meditarranean University, Cyprus

[38] Daryabor, A., Arazpour, M., Sharifi, G., Bani, M. A., Aboutorabi, A., & Golchin, N. (2017). Gait and energy consumption in adolescent idiopathic scoliosis: A literature review. Annals of physical and rehabilitation medicine, 60(2), 107-116.

[39] Wilczyński, J., Habik, N., Paprocki, M. J., Rychter, P., Wilczyński, I., & Dworakowska, D. (2017). Scoliosis compensation and postural responses in school girls. Journal of Education, Health and Sport, 7(8), 218-232.