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Scapulothoracic kinematic pattern in the shoulder pain and scapular dyskinesis: A principal component analysis approach

Denise Martineli Rossi [a], Renan Alves Resende [b], Sérgio Teixeira da Fonseca [b], Anamaria Siriani de Oliveira [a,*]

[a] University of São Paulo, Ribeirão Preto Medical School, Department of Health Sciences, Ribeirão Preto, SP, Brazil
[b] Universidade Federal de Minas Gerais, School of Physical Education, Physical Therapy and Occupational Therapy, Department of Physical Therapy, BH, Brazil

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ABSTRACT

The relationship between shoulder pain and scapular dyskinesis (SDK) is unclear. Differences between groups with and without SDK have been demonstrated, focusing on the amount of scapular motion at specific degrees of humeral elevation. However, this approach does not consider the temporal information and shape of the scapular motion temporal series. Principal Component Analysis (PCA) may clarify this variability and advance current understanding of 'abnormal' movement patterns. This study aimed to evaluate the scapular kinematics in patients with shoulder pain and in asymptomatic participants with and without SDK using PCA. Data were collected in 98 participants separated in four groups: *Pain + SDK* (n = 24), *Pain* (n = 25), *No Pain + SDK* (n = 24), and *No Pain* (n = 25). Scapulothoracic kinematic data were measured with an electromagnetic tracking device during arm elevation and lowering phases. PCA and analysis of variance were used to compare the groups. The *No Pain + SDK* group had a progressive increasing in anterior tilt over the elevation phase compared to the *Pain* (effect size = 0.79) and *No Pain* (effect size = 0.80) groups. During the arm-lowering, the *Pain + SDK* group had a progressive increasing in anterior tilt over this phase in comparison to the *No Pain + SDK* group (effect size = 0.68). Therefore, PCA demonstrated differences in the scapular anterior tilt related to SDK and shoulder pain. The presence of SDK revealed a scapular pattern with progressive increasing in anterior tilt over the elevation phase. However, during the arm-lowering phase, asymptomatic participants with SDK changed their motion pattern, unlike the symptomatic group, reinforcing the suggested association between scapular modifications and shoulder symptoms.

1. Introduction

Modifications in scapular kinematics during arm movements are related to shoulder pain (Keshavarz et al., 2017). Traditionally, comparisons between groups with and without changes in scapular kinematics are restricted to the scapular motion at specific angles of humeral elevation. Previous studies have demonstrated, for example, increased scapular internal rotation at 120° of humeral elevation in patients with clinical scapular dyskinesis (SDK) and shoulder pain (Lopes et al., 2015). In addition, individuals with SDK demonstrated increased scapular internal rotation and anterior tilt at 120°, 90°, 60°, and 30° during arm lowering in comparison to individuals without SDK (Huang et al., 2015). Although the assessment of discrete scapular angles allows the identification of scapular motion changes related to shoulder pain, this approach fails to consider other movement characteristics, such as the temporal information and the shape of the time-series throughout the entire scapular range of motion (Spinelli et al., 2015). The discrete data approach may discard important information by not considering the collinearity and substantial variability present in the biomechanical time-series (Robertson et al., 2014).

A direct relationship between shoulder symptoms and SDK is still uncertain (Kibler et al., 2013; McQuade et al., 2016; Willmore and Smith, 2016). A previous study has demonstrated that the prevalence of SDK is higher in overhead sports athletes than in non-overhead sports athletes (Burn et al., 2016). However, there is no evidence of increased prevalence of SDK in individuals with shoulder pain compared with asymptomatic individuals (Plummer et al., 2017). In addition, previous studies have demonstrated that SDK is not a risk factor for the development of shoulder pain/injury in high school baseball players (Myers et al., 2013) and baseball pitchers (Shitara et al., 2017). On the other hand, Hickey

* Corresponding author at: 3900 Bandeirantes Avenue, Monte Alegre, 14049-9000 Ribeirão Preto, São Paulo, Brazil.
E-mail address: siriani@fmrp.usp.br (A.S. de Oliveira).

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et al. (2017) demonstrated that overhead sports athletes with SKD had a 43% increase in the risk of shoulder pain. Therefore, it is not clear if SKD is associated with shoulder pain and injury or if it is the result of normal movement variability.

A relevant issue regarding SDK is the definition of 'normal' and 'abnormal' scapular motion, considering the high degree of variability within and between subjects, the possibility of individuals' adaptive strategies, and optimization (McQuade et al., 2016; Willmore and Smith, 2016). Multivariate statistical techniques, such as the Principal Component Analysis (PCA), may provide more information about this movement variability and advance the current understanding of 'normal/abnormal' movement patterns. PCA considers the whole time-series and provides parameters that represent motion patterns better than parameters based on arbitrary selection of discrete values (Astephen and Deluzio, 2004; Daffertshofer et al., 2004). PCA has been widely used in gait studies (Deluzio and Astephen, 2007; Resende et al., 2017, 2015), but has not been previously used to analyze scapular kinematic time-series (Huang et al., 2017; Roren et al., 2015). More specifically, previous studies have either used PCA with discrete scapular angles (Huang et al., 2017) or have evaluated coordination between scapular linear and angular movements (Roren et al., 2015). Considering that it is not clear whether SKD is the result of a typical movement variability or a risk factor for the development of pathological shoulder conditions, the use of PCA may help solve this issue. In the present study, we used PCA as a data reduction approach for the entire scapular kinematic time-series, including participants with different combinations of SKD and shoulder pain. Thus, this study evaluated the scapular kinematic pattern in patients with shoulder pain and also in asymptomatic participants with and without SDK. We hypothesized that the scapular movement time-series of individuals with and without SDK would have different patterns of scapular internal rotation and anterior tilt.

2. Material and methods

2.1. Participants

This cross-sectional study evaluated 100 participants (50 shoulder pain, 50 asymptomatic; age 18–60 years). The participants with shoulder pain were recruited from the local public health service based on the following inclusion criteria: self-report of anterolateral shoulder pain lasting for more than 1 week, pain with active arm elevation, and at least two positive impingement signs (Hawkins-Kennedy, Neer, or Jobe tests, and pain on resisted lateral rotation) (Michener et al., 2009). The exclusion criteria were: previous shoulder surgery, full tear of rotator cuff muscles evidenced by imaging, or inability to perform the procedures for data collection. Asymptomatic participants were from a convenience sample and had no history of shoulder pain or previous pathology. All participants provided informed consent and the study was approved by the local Ethics Research Committee (protocol 4799/2014).

The participants were separated into four groups (25 participants each), considering the presence of symptoms and SDK: participants with shoulder pain and SDK (*Pain + SDK* group), participants with shoulder pain but without SDK (*Pain* group), participants without shoulder pain but with SDK (*No Pain + SDK* group), and participants without shoulder pain or SDK (*No Pain* group).

Anthropometric and demographic data, hand dominance, and physical activity level using the International Physical Activity Questionnaire (IPAQ) were collected from all participants. The symptomatic participants rated their pain using the Numeric Pain Rating Scale (NPRS) and answered the Shoulder Pain and Disability Index questionnaire (SPADI) (Martins et al., 2010).

2.2. Scapular dyskinesis assessment

A trained physiotherapist evaluated the presence of SDK and demonstrated moderate intrarater reliability (0.79 kappa) and good interrater reliability (0.89 kappa) (Rossi et al., 2017). The physiotherapist was not blinded to the presence/absence of shoulder pain among the participants. The participants performed ten cycles of arm elevation and lowering in the sagittal plane by holding dumbbells weighted according to their body mass (1.5 kg for body mass < 68.1 kg; 2.5 kg for body mass > 68.1 kg). The physiotherapist could observe the scapula from any view point, with freedom to move during the test, but staying at approximately 2 m from the participants. Both scapulae were evaluated, separately. First, the physiotherapist used the Yes/No classification, as recommended by the current "Scapular Summit" consensus (Kibler et al., 2013) to categorize the participants according to SDK presence or absence. Second, participants were also categorized based on altered specific scapular movement (Kibler et al., 2002) as Type 1 (posterior projection of the inferior medial scapular border), Type 2 (posterior projection of the entire medial scapular border), Type 3 (elevation of the superior border and shoulder shrug without significant scapula winging), or Type 4 (scapular border attached to the thorax during movement) SDK (Rossi et al., 2017). Uhl et al. (2009) demonstrated that the validity of the Yes/No classification had high sensitivity (74–78%) and low specificity (31–38%), while the 4-types classification had sensitivity ranging from 10% to 54% and specificity ranging from 62% to 94% (Uhl et al., 2009). To be categorized in one of the study groups, the participants were evaluated using both classifications (Rossi et al., 2017). Considering their sensitivity and specificity, the use of the two classification systems to identify individuals with or without SDK is a stronger approach compared with the use of either classification alone.

2.3. Kinematic data

We collected scapular kinematic data using an electromagnetic tracking device (Polhemus 3 Space, Colchester, USA) and MotionMonitor software (Innovative Sports Training, Chicago, USA). This electromagnetic device has a root mean square accuracy of 0.076 cm for sensor position and 0.15° for sensor orientation. The transmitter was fixed 110 cm above the floor and emitted an electromagnetic signal to the sensors attached to the participant. The sensors were attached to the sternum, to the flat surface of the acromion process, and just below the insertion of the deltoid muscle. Another sensor was attached to a pointer to manually digitize the bone landmarks to create local coordinate systems on the thorax (suprasternal notch, xiphoid process, spinal processes of C7 and T8), scapula (acromial angle, root of the spine, inferior angle), and humerus (medial and lateral epicondyle) (Wu et al., 2005).

The three-dimensional position and orientation of each sensor were collected at 120 Hz. Sensor orientations were rotated to anatomically define scapular rotations using a Euler sequence. We used the y-x-z sequence to describe the scapular orientation relative to the thorax, with the z-axis defined in the scapular plane, from the scapula spine root to the posterolateral acromion; the x-axis was perpendicular to the scapular plane, and the y-axis was perpendicular to the z-axis and x-axis (Wu et al., 2005). We used the x-z-y sequence to describe the humeral elevation relative to the thorax, with the x-axis pointing anteriorly (humeral elevation), z-axis pointing laterally (elevation plane), and y-axis superiorly (axial rotation) (Phadke et al., 2011).

Data were recorded with the participants standing in a relaxed position and during the arm elevation and lowering phases in the sagittal plane. Participants were instructed to elevate and lower the arm during a period of 2 s each without holding dumbbells. Participants performed ten trials, but only the last three were analyzed. In the *No Pain + SKD* group, kinematic data were analyzed in the side that had SKD or in the dominant side if SKD was bilateral. In the *Pain + SKD* and *Pain* groups, the symptomatic side or the worst pain side was considered in the analysis. In the *No Pain* group, the evaluated side was randomly defined. In this group, 16 participants had the dominant side analyzed and 9 participants had the data of the non-dominant side used for analysis.

2.4. Data reduction

Kinematic data were processed using the Matlab software (Mathworks®). Raw kinematic data were filtered using a low-pass fourth-order Butterworth filter with a cut-off frequency of 6 Hz. The following scapular kinematic variables were calculated: internal rotation, upward rotation, and anterior tilt. The phase between 20° and 120° of the humerothoracic angle was defined as the arm elevation phase, and the phase between 120° and 20° of humerothoracic angle was the arm-lowering phase. Scapular rotation variables were normalized to 101 data points, one for each percentage of both phases.

2.5. Data analysis

2.5.1. Principal component analysis (PCA)

PCA was performed, separately, on the three kinematic variables in the two phases (i.e., elevation and lowering) for 98 participants, since we excluded two participants' data (one from the *Pain + SDK* and one from the *No Pain + SDK* group) because they did not attain 120° of humerothoracic elevation. Six matrices (98 participants X 101 temporal observations throughout the movement phase) were produced. Each row represented the time-series of each participant, and each column represented the values of the specific scapular variable at each percentage of the movement phase.

The covariance matrix was calculated from the mean-centered of each original data matrix. Following this, an eigenvalue decomposition of this covariance matrix was performed by the PC model $Z = [U^tX]$, where U is the transformation matrix that realigned the original data into a new coordinate system. The columns of U were the eigenvectors of the covariance matrix of the original dataset and were designated PC loading vectors (Deluzio and Astephen, 2007). The PCs were obtained and ordered according to the amount of variance explained in the original data. The amount of variance of each PC was computed by dividing each eigenvalue for each equivalent PC by the trace of the covariance matrix (Resende et al., 2016). Because of the highly covariant characteristic of the scapulothoracic kinematic time-series, the first two PCs were sufficient to account for at least 90% of the data variance in each original time-series.

2.5.2. Statistical analysis

The methods used to compute the PCs scores of the participants of the four groups are described in the Supplementary Material. These PC scores were compared between groups using analysis of variance (one-way ANOVA) and Tukey-Kramer post hoc test, one ANOVA for each PC of each scapular motion. A chi-squared test was applied to categorical variables of sample characterization, and ANOVA repeated measure was used to compare the pain intensity pre-and post-kinematic evaluation between groups. The normal distribution and homogeneity of variance of the residuals were confirmed by Kolmogorov-Smirnov and Shapiro-Wilk tests and by Levene's test, respectively. The significance level was set at 0.05. The effect sizes (ES) of the comparisons with statistically significant differences were calculated by dividing the difference between the means of the two groups by their pooled standard deviation. The effect sizes were interpreted as follows: $ES \leq 0.5$: small; $0.5 < ES \leq 0.8$: moderate; and $ES > 0.8$: large (Cohen, 1988).

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jbiomech.2018.07.010.

The method of single component reconstruction was used to interpret the differences between groups in PC scores (Brandon et al., 2013). This method is described in the Supplementary Material.

3. Results

3.1. Participants

This study included 49 symptomatic and 49 asymptomatic participants (kinematic data from two participants were excluded). Table 1 describes anthropometric, demographic, and physical activity level data from all participants and the pain intensity and shoulder disability from symptomatic participants. Asymptomatic participants with SDK (*No Pain + SDK*) were younger than symptomatic participants (*Pain + SDK* and *Pain*) ($p = 0.01$, $F = 12.9$) and had a lower body mass index ($p = 0.01$, $F = 6.9$) than all other groups (Table 1). There was no difference between groups in the dominance distribution according to the evaluated side (chi-squared, $p = 0.187$). Most of the participants were active or minimally active. The *No Pain* group had the highest and the *Pain + SKD* group had the lowest percentage of very active participants, 32% and 4%, respectively (Table 1).

Both symptomatic groups demonstrated similar SPADI total scores. Most symptomatic participants had mild or moderate pain. In the *Pain + SDK* and *Pain* groups, 37% and 20% of the participants had severe pain, respectively. There were no differences in pain intensity distribution (i.e., severe, moderate, and mild pain) between the symptomatic groups (chi-squared, $p = 0.16$). The pain intensity increased in both groups after the kinematic evaluation ($p = 0.01$, $F = 222.4$). The changes in the numeric pain rating scale were 5 (SD 2.29) points (IC: 3.9; 5.9) in the *Pain + SKD* group, and 4 (SD 2.2) points (IC: 3.2; 5.1) in the *Pain* group. There was no interaction between groups and the change in the pain intensity pre- and post-kinematic evaluation ($p = 0.27$, $F = 1.28$) (Table 1).

In the 4-types classification of SDK, the participants of the *Pain + SKD* group were classified as having SDK Type 1 (75%), Type 2 (17%) or Type 3 (8%). In the *No Pain + SDK* group, participants were classified as having SDK Type 1 (96%) or Type 2 (4%). In the *Pain* and *No Pain* groups, all of the participants were classified as SKD Type 4 (i.e., not having SKD).

3.2. Scapular kinematics

Fig. 1 shows each group mean time-series data for scapular internal rotation, upward rotation, and anterior tilt during arm elevation and lowering phases. Statistical analysis of the PCs scores demonstrated between-group differences only for scapular anterior tilt during arm elevation ($p = 0.04$; $F = 2.99$) and lowering ($p = 0.05$; $F = 2.79$). Table 2 shows the groups mean score values for PC1 and PC2 for the three scapular rotations during arm elevation and arm lowering.

During the arm elevation phase, the *No Pain + SDK* group had a higher PC2 score than the *Pain* and *No Pain* groups. The mean differences between the *No Pain + SDK* and the *Pain* and *No Pain* groups were 16.31 (confidence interval [CI]: 0.66; 31.97) and 16.02 (CI: 0.75; 31.29), and effect sizes: 0.79 and 0.80, respectively. The mean score values for each group represented the degree to which each group expressed the specific pattern of variance captured by each PC.

Table 1
Participants characteristics.

	Pain + SDK (n = 24)	*Pain* (n = 25)	*No Pain + SDK* (n = 24)	*No Pain* (n = 25)
Age (years)	47.21 (8.6)	48.60 (8.7)	34.38 (8.6)*	40.76 (10.5)
Height (cm)	166 (0.1)	165 (0.1)	169 (0.1)	171 (0.1)
Mass (kg)	69.98 (10.2)	73.03 (15.3)	64.73 (10.4)	73.34 (12.1)
BMI (kg/m^2)	25.50 (3.4)	26.40 (3.0)	22.70 (2.5)†	25.07 (2.7)
Gender (male)	12 (50%)	9 (36%)	9 (36%)	13 (54%)
Evaluated side same as dominant side	9 (36%)	16 (64%)	12 (50%)	16 (64%)
IPAQ				
Inactive	4 (17%)	8 (32%)	5 (21%)	1 (4%)
Minimally active	6 (25%)	10 (40%)	7 (29%)	8 (32%)
Active	14 (58%)	6 (24%)	10 (42%)	8 (32%)
Very active	0 (0%)	1 (4%)	2 (8%)	8 (32%)
NPRS (0–10)				
Mild pain (1–3)	10 (42%)	9 (36%)	–	–
Moderate pain (4–6)	5 (21%)	11 (44%)	–	–
Severe pain (7–10)	9 (37%)	5 (20%)	–	–
SPADI (0–100)				
Disability	42.91 (19.5)	45.06 (20.7)	–	–
Pain	65.31 (17.2)	56.78 (18.3)	–	–
Total score	51.58 (17.2)	49.66 (17.6)	–	–

The values are given as the mean (standard deviation) and frequency (percentage).
SDK: scapular dyskinesis; BMI: Body Mass Index; NPRS: Numeric Pain Rating Scale; SPADI: Shoulder Pain and Disability Index; IPAQ: International Physical Activity Questionnaire.
* $p < 0.05$ for *No Pain + SDK* lower than *Pain + SDK* and *Pain*.
† $p < 0.05$ for *No Pain + SDK* lower than other groups.

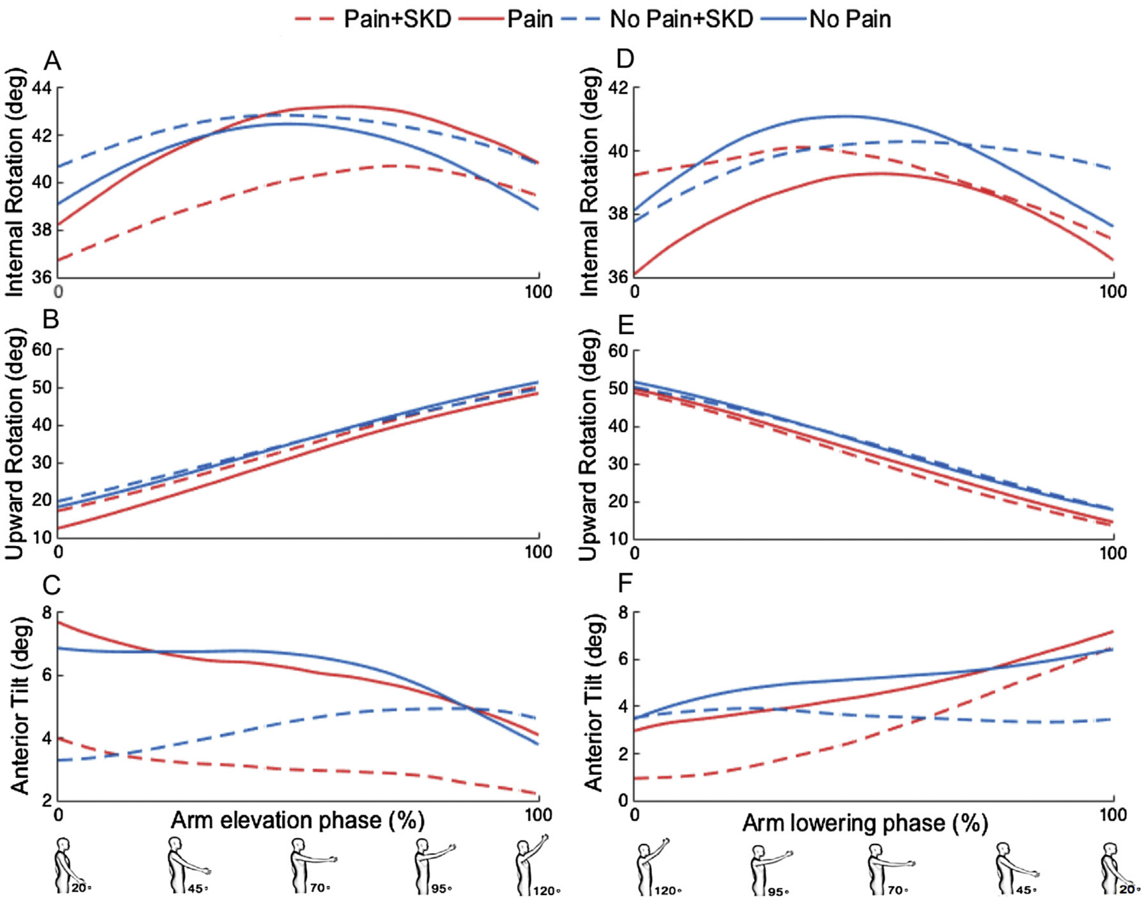

Fig. 1. Mean time-series of each group for the three scapular rotations during arm elevation and lowering phases (%). (A) Internal rotation mean time-series of each group during arm elevation. (B) Upward rotation mean time-series of each group during arm elevation. (C) Anterior tilt mean time-series of each group during arm elevation. (D) Internal rotation mean time-series of each group during arm lowering. (E) Upward rotation mean time-series of each group during arm lowering. F) Anterior tilt mean time-series of each group during arm lowering. Red lines represent symptomatic groups, and blue lines represent asymptomatic groups. Solid lines represent groups without scapular dyskinesis (SDK) and dashed lines represent groups with SD. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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Table 2
Principal components (PC), the percentage of variance explained and the respective average scores and standard deviation of each group for the three scapular rotations during arm elevation and arm lowering. Results of the ANOVAs are also presented.

	PC	Var. Exp. (%)	*Pain + SDK* (n = 24)	*Pain* (n = 25)	*No Pain + SDK* (n = 24)	*No Pain* (n = 25)	p-value (F)
Ele. phase							
Int. rot.	1	90.86	−15.49 (95.6)	7.25 (63.7)	8.47 (93.4)	−0.52 (76.7)	0.74 (0.4)
	2	7.96	9.25 (22.9)	1.88 (28.1)	−5.67 (26.6)	−5.32 (16.8)	0.11 (2.1)
Up. rot.	1	79.13	0.30 (93.2)	−26.71 (68.1)	14.06 (66.5)	12.93 (73.4)	0.21 (1.6)
	2	19.45	0.44 (51.7)	7.38 (33.8)	−9.35 (36.1)	1.18 (26.9)	0.50 (0.8)
Ant. tilt	1	87.97	−18.82 (75.7)	10.57 (60.3)	−4.23 (75.5)	11.56 (51.5)	0.34 (1.1)
	2	10.77	3.24 (27.9)	−6.44 (21.5)	9.87 (19.7)	−6.15 (20.5)	0.04 (3.0)*
Low. phase							
Int. rot.	1	90.05	0.51 (76.6)	−10.43 (47.3)	3.64 (93.5)	6.44 (78.2)	0.87 (0.2)
	2	8.87	5.49 (24.8)	−0.53 (20.7)	−5.50 (26.1)	0.53 (22.1)	0.45 (0.9)
Up. rot.	1	82.63	−23.67 (92.0)	−9.29 (74.7)	17.73 (71.2)	15.53 (82.7)	0.23 (1.5)
	2	15.62	0.87 (48.9)	0.96 (23.8)	−3.94 (39.8)	2.00 (25.1)	0.94 (0.1)
Ant. tilt	1	86.53	−11.84 (77.5)	5.24 (57.8)	−4.07 (72.9)	10.04 (54.4)	0.66 (0.5)
	2	12.01	6.94 (29.9)	3.97 (22.7)	−10.97 (22.7)	−0.11 (19.3)	0.04 (2.6)*

SDK: scapular dyskinesis; Ele.: elevation; Low.: Lowering; Var. Exp.: Variance Explained; Int. rot.: internal rotation; Up. rot.: upward rotation; Ant. tilt.: anterior tilt.
* $p < 0.05$ for the *No Pain + SDK* group higher than the *Pain* and *No Pain* groups.

Fig. 2A shows each group's mean time-series for scapular anterior tilt during arm elevation. Fig. 2B shows the PC2 loading vector that had large coefficients (i.e. distant from zero) at the beginning and end of this phase, which means that these portions of the arm elevation phases contributed more to the feature captured by PC2. The *No Pain + SDK* group had higher PC2 score than the *Pain* and *No Pain* groups during the arm-elevation phase (Table 2). As demonstrated in Fig. 2C, the *No Pain + SDK* group (High PC2 score) had smaller scapular anterior tilt at the beginning of the elevation phase and greater scapular anterior tilt at end of this phase in comparison to the *Pain* and *No Pain* groups (Low PC2 score). In other words, the *No Pain + SDK* group had increased anterior tilt at the end of arm-elevation phase in comparison to the beginning of this phase, while the *Pain and No Pain* groups had the opposite pattern, that is, smaller anterior tilt at the end of this phase in comparison to the beginning of this phase. In addition, the *Pain* and *No Pain* groups (Low PC2 score) had greater overall range of anterior tilt throughout the elevation phase in comparison to the *No Pain + SDK* group (High PC2 score). During the arm-lowering phase, the *Pain + SDK* group had greater PC2 score than the *No Pain + SDK* group (mean difference, 17.91; CI: -0.13, -35.94; effect size: 0.68) (Table 2).

Fig. 3A shows the mean time-series of each group for scapular anterior tilt during the arm-lowering phase. Fig. 3B shows the PC2 loading vector for the scapular anterior tilt data during this phase. The PC2 loading vector had large coefficients (i.e. distant from zero) at the beginning and at the end of this phase, which means that these portions of the arm-lowering phase contributed more to the feature captured by PC2. The *Pain + SDK* group had higher PC2 score than the *No Pain + SDK* group during this phase (Table 2). As demonstrated in Fig. 3C, the *Pain + SDK* group (High PC2 score) had smaller scapular anterior tilt at the beginning of the lowering phase and greater scapular anterior tilt at the end of this phase in comparison to the *No Pain + SDK* group (Low PC2 score). In other words, the *Pain + SDK* group had increased anterior tilt at the end of arm-lowering phase in comparison to the beginning of this phase, while the *No Pain + SDK* group had the opposite pattern, that is, smaller anterior tilt at the end of this phase in comparison to the beginning of this phase. In addition, the *Pain + SDK* group (High PC2) had greater overall range of anterior tilt throughout the arm-lowering phase than the *No Pain + SDK* group (Low PC2 score).

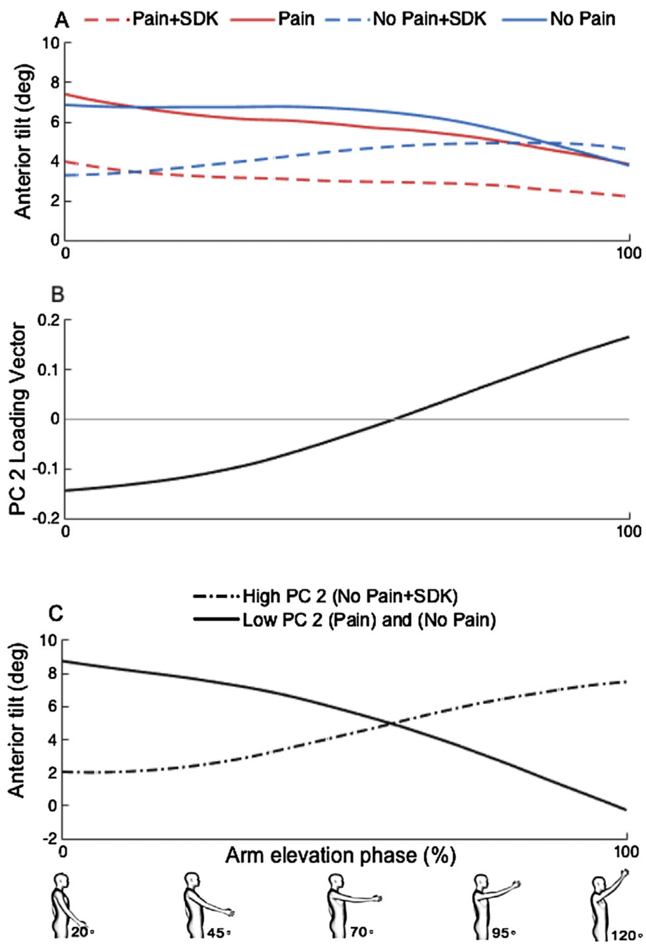

Fig. 2. (A) Scapular anterior tilt mean time-series of each group during arm elevation phase (%). Red lines represent symptomatic groups, and blue lines represent asymptomatic groups. Solid lines represent groups without scapular dyskinesis (SDK) and dashed lines represent groups with SD. (B) Magnitudes of the principal component (PC) loading vector. (C) Reconstructed time-series that represent high and low PC scores. In this case, high score (dashed line) characterizes the *No Pain + SDK* group, and low score (solid line) represents the *Pain* and *No Pain* groups. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

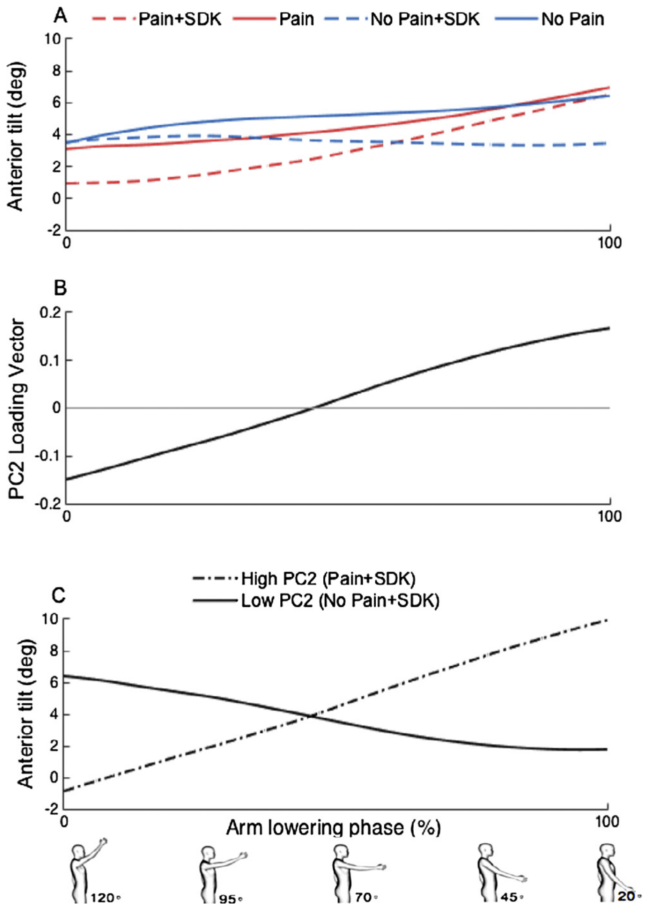

Fig. 3. (A) Scapular anterior tilt mean time-series of each group during arm lowering phase (%). Red lines represent symptomatic groups, and blue lines represent asymptomatic groups. Solid lines represent groups without scapular dyskinesis (SDK) and dashed lines represent groups with SD. (B) Magnitudes of the PC loading vector. (C) Reconstructed time-series that represent high and low PC scores. In this case, high score (dashed line) characterizes the *Pain + SDK* group, and low score (solid line) represents the *No Pain + SDK* group. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

In this study, the use of PCA as a data reduction and interpretation method allowed the identification of different characteristics in the pattern of the original scapular kinematics data. Each PC was related to a particular shape change in the scapular angles time-series. PC2 captured the overall range of anterior/posterior tilt throughout the arm elevation and lowering phases. In addition, PC2 captured opposite movement pattern between the beginning and end of these phases. During the arm-elevation phase, the participants of the *No Pain + SDK* group had greater anterior tilt at the end in comparison to the beginning of this phase, while the participants without SDK (i.e. *No pain and Pain* groups) had the opposite pattern. In addition, the *No Pain + SDK* group had smaller range of anterior tilt than the participants without SDK. During the arm-lowering phase, the symptomatic participants with SDK had greater anterior tilt in the end in comparison to the beginning of this phase, while the asymptomatic participants with SDK had the opposite pattern. In addition, the symptomatic participants with SDK had greater range of anterior tilt than the asymptomatic participants with SDK.

Increased scapular anterior tilt has already been suggested in asymptomatic (Miachiro et al., 2014) and symptomatic participants (Huang et al., 2015) with SDK Type 1. Huang et al. (2017) used PCA to investigate discrete parameters related to scapular motion in participants with and without SDK. They demonstrated positive correlation between the occurrence of SDK Type 1 and increased anterior tilt (Huang et al., 2017). Thus, the high proportion of individuals with SDK Type 1 in both SDK groups, symptomatic and asymptomatic, may have contributed to the differences in scapular anterior tilt observed between the groups with and without SKD during arm elevation.

The literature also demonstrates kinematic differences between participants with and without shoulder pain, independent of SDK clinical evaluation. Studies revealed reduced scapular upward rotation, increased scapular internal rotation (Keshavarz et al., 2017; Timmons et al., 2012), and increased scapular anterior tilt (Lefèvre-Colau et al., 2017) in subacromial impingement syndrome patients compared to asymptomatic individuals. Ludewig and Cook (2000) suggested that although the anterior tilt range of motion is smaller than the upward rotation, an increased anterior tilt may be more critical for maintaining adequate clearance of the rotator cuff tendons, increasing the potential for impingement (Ludewig and Cook, 2000). In our study, the asymptomatic group with SDK had a distinct anterior tilt motion pattern, when compared to the symptomatic group. During arm-lowering, participants with SDK and shoulder pain had the highest overall range of anterior tilt and progressive increase in anterior tilt throughout this phase. Although previous studies comparing people with and without subacromial impingement syndrome did not include the assessment of SDK, the observed relationship between altered scapular kinematics and shoulder pain is in agreement with our findings of increased anterior tilt pattern over the arm-lowering phase in the *Pain + SDK* group.

There were no between-group differences for scapular upward and internal rotation. The PCA revealed that each data point of the scapular kinematic time-series was highly correlated to its neighboring data point, which can be confirmed by the high percentage of variance explained by PC1 and by PC2. Amidst this collinearity, there was a substantial variability in the scapular kinematic data (i.e., variability in scapular rotation within and between groups). Due to this high variability, it was demonstrated that the groups differed only in scapular anterior tilt behavior. In opposition to our results, Tate et al. (2009) showed reduced scapular upward rotation (approximately 9°) at 30° and 60° during arm elevation in asymptomatic overhead athletes with obvious SDK compared to athletes without SDK (Tate et al., 2009). In addition, Lopes et al. (2015) found a modest increase in scapular internal rotation in patients with subacromial impingement syndrome and obvious SDK compared to patients without SDK. By analyzing discrete parameters, they demonstrated that individuals with obvious SDK had increased scapular internal rotation (approximately 3°) only at 120° of humerothoracic elevation, during arm elevation and lowering (Lopes et al., 2015). However, both studies used the Scapular Dyskinesis Test, in which participants are classified as obvious, subtle, or normal according to the severity of scapular movement disorder. Moreover, the mean differences were smaller than the standard error of measurement and than the minimal detectable change (Haik et al., 2014; Lopes et al., 2015). Therefore, these results should be cautiously interpreted. Since the current study is the first using PCA as a data reduction and interpretation tool for the entire scapular kinematic time-series, it is not possible, at present, to determine the minimal detectable changes of the different behaviors of the scapular kinematic variables.

This study had some limitations that include not blinding the examiner to the presence of shoulder pain, since a previous study have demonstrate that if influences SKD evaluation (Plummer et al., 2017). Moreover, the asymptomatic participants with SDK were younger than the symptomatic participants and had a lower

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body mass index compared to the other groups. A previous study has demonstrated that asymptomatic young people demonstrate a higher range of scapular upward rotation and internal rotation compared to older people (Roldán-Jiménez and Cuesta-Vargas, 2016). However, in the same study, age did not influence scapular anterior tilt motion, which was the variable that demonstrated between-group differences in the present study. Furthermore, we did not control arm movement velocity during the elevation and lowering phases. However, the humerothoracic and scapular measurements were time-normalized and arm elevation velocity apparently does not influence scapulothoracic kinematics (Fayad et al., 2006). Finally, considering the psychometric properties of the methods used to evaluate SDK (Uhl et al., 2009), some participants might have been misclassified regarding SDK. However, the methods used to assess SDK followed the recommendations of the "Scapular Summit" consensus (Kibler et al., 2013).

5. Conclusion

This study demonstrated that asymptomatic participants with SDK had increased anterior tilt during the elevation phase compared to participants without SDK. During the arm-lowering phase, asymptomatic participants with SDK had different scapular motion and showed reduced range of anterior tilt compared to symptomatic participants with SDK, who had a progressive increase in anterior tilt during this phase. The use of PCA as a data reduction and interpretation tool for scapular kinematics allowed statistical comparisons between groups without redundancy and preserved temporal information in a non-arbitrary manner. Therefore, PCA may be used in future studies investigating scapular kinematic patterns.

Conflict of interest statement

The authors have no conflicts of interest to declare.

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