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# Three-dimensional scapular kinematics during open and closed kinetic chain movements in asymptomatic and symptomatic subjects☆

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ABSTRACT

The combination of open kinetic chain (OKC) and closed kinetic chain (CKC) exercises is commonly recommended in shoulder rehabilitation, aiming at improving strength and sport-specific performance. This study aimed to investigate the three-dimensional (3-D) scapular kinematics and bilateral symmetry of scapular motion during dynamic OKC and CKC movements in asymptomatic and symptomatic shoulders. Fifty subjects with unilateral shoulder pain (symptomatic subjects diagnosed with subacromial impingement syndrome, $n=20$) or without shoulder pain during active shoulder elevation (asymptomatic subjects, $n=30$) participated in the study. Furthermore, 3-D scapular kinematics were recorded using an electromagnetic tracking device in the sagittal plane of shoulder elevation for both the OKC and CKC conditions performed with slings. Data for scapular kinematics and symmetry angle (SA) were analyzed at 30°, 45°, 60°, 90°, and 120° of humerothoracic elevation. Analysis of variance models and Student's *t*-test were used to make comparisons between conditions. In general, the scapula was more externally rotated, upwardly rotated and anteriorly tilted for asymptomatic shoulders, and more upwardly rotated for symptomatic shoulders during CKC shoulder elevation. Further, comparisons of SA obtained during OKC and CKC movements revealed that during CKC, scapular motion was more symmetrical for upward–downward rotation and anterior–posterior tilt in asymptomatic shoulders and for anterior–posterior tilt in symptomatic shoulders, especially above 90° humerothoracic elevation. Differences in scapular motion during the CKC condition were in a specific pattern and enhanced symmetry, which would be considered to be a position less likely to produce compression of the rotator cuff tendons for both training in asymptomatic populations and for treatment in early rehabilitation of patients, such as those who have shoulder impingement syndrome.



## 1. Introduction

The definitions of OKC and CKC movements vary across studies, and it is widely accepted that CKC requires weight-bearing position of the extremity by fixing the terminal segment or the terminal segment meets some considerable external resistance that prohibits or restrains its free motion (Steindler, 1955). On the other hand, OKC does not require fixing of the terminal segment and allows the terminal segment to move freely (Gowitzke and Milner, 1988; Lephart and Henry, 1996). Biomechanical studies have supported the rationale for the advantages of applying CKC exercises, which have been widely examined for the lower extremities (Beynnon et al., 1997; Escamilla et al., 1998; Lutz et al., 1993; Wilk et al., 1996; Yack et al., 1993) and particularly recommended for early anterior cruciate ligament reconstruction rehabilitation (Wright et al., 2008). Isometric (static) or dynamic CKC exercises often involve multijoint movements and weight-bearing conditions that effect the biomechanical and neuromuscular demands of the body (Tucker et al., 2010). A significant amount of agonist–antagonist muscular cocontraction exists around joints (Pincivero et al., 2000; Stensdotter et al., 2003), in addition to increased articular compressive forces (Lutz et al., 1993) during CKC performance. Recently, CKC movements are considered to be one of the commonly performed exercises for the upper extremities, using simply the ground and the wall, or via specific devices such as ropes and slings, aiming at addressing shoulder stability and improving joint position sense (Kibler, 2000; Martins et al., 2008; Rogol et al., 1998).

☆Gazi University Institutional Review Board approved the protocol for this study (KN:156).

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For the upper extremities, some studies have investigated muscular activation levels during OKC and CKC movements. Dillman et al. (1994) indicated that CKC exercises have similar biomechanics for prime movers, such as pectoralis and deltoid muscular activity, compared with OKC. However, research has shown that upper extremity closed-chain exercises, such as push-ups, evolve high levels of serratus anterior activation in healthy subjects (Lear and Gross, 1998) and subjects with secondary shoulder impingement (Tucker et al., 2010). Interestingly, during CKC, there is absence of a muscle imbalance between the serratus anterior and upper trapezius, previously demonstrated in shoulder impingement syndrome during various OKC activities (Tucker et al., 2010).

The upper, middle, and lower trapezius with serratus anterior function as a force couple to provide scapular control and upward rotation during humeral elevation (Neumann, 2013). Alongside alternations in the force couple activations and timing, alternations in kinematics, such as decreased upward rotation and external rotation, as well as asymmetrical motion, are considered to be some of the impairments that have been associated with shoulder pain and have been suggested as mechanisms underlying shoulder impingement syndrome (Ludewig and Reynolds, 2009). Even though the findings in the literature concerning scapular kinematics symmetry between dominant and non-dominant shoulders are contradictory (Matsuki et al., 2011; Morais and Pascoal, 2013; Schwartz et al., 2014; Uhl et al., 2009; Yoshizaki et al., 2009), Kibler (1998) suggested that symmetry in scapular motion should be considered as a criterion for normal scapular motion. Therefore, during dynamic upper extremity movements, the bilateral symmetry of scapular motion and winging should be assessed and scapular control impairments should be addressed in shoulder rehabilitation (Kibler et al., 2013).

For improving strength and sport-specific performance as well as for preventing injuries, a combination of OKC and CKC exercises have commonly been recommended in shoulder rehabilitation (McMullen and Uhl, 2000). Several studies have recommended applying CKC exercises in shoulder rehabilitation (Rogol et al., 1998) and have examined the muscle activation (Hardwick et al., 2006; Tucker et al., 2010); however, the scientific rationale for scapular kinematics has not been reported. Therefore, this study aimed to investigate 3-D scapular kinematics and scapular symmetry during dynamic OKC and CKC movements in asymptomatic and symptomatic shoulders. The hypotheses of this study were as follows:

- 3-D scapular position and orientation differs during dynamic OKC and CKC upper extremity movements and
- scapular symmetry differs during dynamic OKC and CKC upper extremity movements.

## 2. Material and methods

### 2.1. Subjects

Fifty subjects with unilateral shoulder pain (symptomatic subjects diagnosed with subacromial impingement syndrome; $n=20$; mean pain severity during elevation on visual analog scale: $2.2 \pm 1.7$ cm; mean SPADI score: $25.5 \pm 19.1$ points) or without shoulder pain (asymptomatic subjects; $n=30$) during active shoulder elevation participated in the study (Table 1). All subjects were right-side dominant and had impingement symptoms on their dominant side. The inclusion criteria for participation for all subjects were no limitation in shoulder range of motion and no prior shoulder surgery. Symptomatic subjects, who were diagnosed by a consulting orthopedic surgeon with subacromial impingement syndrome, had been suffering from unilateral shoulder pain at the dominant arm lasting more than six weeks. Subjects with subacromial impingement syndrome enrolled in this trial according to clinical examination were positive for at least two of the following: (1) painful arc during flexion or abduction, (2) Neer (1983) or Hawkins and Kennedy (1980) test, and (3) painful resisted external rotation, abduction or painful Jobe's test (Magee, 1997). Excluded from this study were patients with massive rotator cuff tears, long head of biceps tendon tears, or degenerative joint disorders at the shoulder complex. Asymptomatic subjects were selected from asymptomatic volunteers who had no history of shoulder pain or injury related to upper body and extremities. These subjects had no positive Neer (1983), Hawkins and Kennedy (1980) or apprehension–relocation tests (Tzannes et al., 2004). Subjects were excluded if they had any known systemic or neurological disorders, performed repetitive shoulder movements related to occupation or sports activities on a regular basis, or had a body mass index higher than 30 kg/m$^2$.

**Table 1**
Characteristics of participants.

| | Asymptomatic subjects $n=30$ | Symptomatic subjects $n=20$ |
|---|---|---|
| Age (years) | 23 (1.4) | 26.93 (7.5) |
| Height (m) | 1.7 (0.2) | 1.7 (0.1) |
| Weight (kg) | 69.9 (12.1) | 67 (10.6) |
| Body mass index (kg/m$^2$) | 23 (3.3) | 22.2 (2.3) |
| Gender ($n$) | 12 Female 18 Male | 9 Female 11 Male |

Note: Data given as mean and standard deviation (for age, height, weight and body mass index), or as counted numbers and percentage (gender).

The Gazi University Institutional Review Board approved the protocol for this study, and all subjects were informed of the nature of the study and signed a consent form (KN:156).

### 2.2. Instrumentation

3-D kinematic data for the scapula and humerus were collected with a Flock of Birds electromagnetic tracking device (Ascension Technology Corporation, Shelburne, VT). This system comprises an electronics unit, standard-range transmitter, five sensors (25.4 × 25.4 × 20.3 mm), and one digitizer, interfaced with the Motion Monitor software program (Innovative Sports Training, Inc., Chicago, IL). Data collected with this electromagnetic tracking system are reliable, with calculated trial-to-trial, within-day, without-removal-of-sensors ICC values ranging from 0.82 to 0.99 and 0.72 to 0.99; standard error of measurement values ranging from 0.46° to 1.09° and 0.15° to 1.11° for scapular internal–external rotation, from 0.64° to 1.33° and 0.45° to 1.01° for scapular upward–downward rotation, and from 0.68° to 1.04° and 0.54° to 1.69° for scapular anterior–posterior tilt for asymptomatic and symptomatic subjects, respectively. This method of measuring 3-D scapular kinematics has previously been validated by comparing data obtained from skin sensors to those obtained from acromion-fixed sensors, which were similar, especially below 120° of elevation (Karduna et al., 2001). Data were collected at a rate of 100 Hz per sensor and subsequently filtered using the system's Butterworth filter software, with a 6-Hz low-pass cutoff frequency.

For data collection, five sensors were attached directly to the skin with double-sided adhesive tape and further secured with nonelastic tape (Fig. 1). The thoracic sensor was located over the T1 spinous process, and the scapular sensors were applied to each scapula over the flattest aspect of the postero-lateral aspect of the acromion to reduce artifacts produced by skin movement (Ludewig and Cook, 2000). The humeral sensor for each arm was applied over the postero-lateral aspect of the humerus distal to the triceps muscle belly. The transmitter, mounted on a rigid wooden base, provided a global coordinate system. Participants stood with their arms relaxed while specific bony landmarks were digitized to create an anatomically based local coordinate system. The International Society of Biomechanics standard protocol was followed to define segmental axes and convert the local coordinate system into angular rotations using the Euler angle sequence (Wu et al., 2005). The regression model suggested by Meskers et al. (1998) was used to define the rotation center of the glenohumeral joint.

### 2.3. Experimental procedure

The subjects were familiarized with selected OKC and CKC shoulder movements. OKC shoulder elevation was performed while the subject was standing and the elbow was in the 90° flexed position (Fig. 2). The subject was asked to perform bilateral, full shoulder flexion against gravity and straighten the elbow throughout the movement. Dynamic and axially loaded CKC shoulder elevation was performed with Redcord slings (Redcord Trainer, Redcord AS, Staubø, Norway) while the subject stood directly under the suspension point with the elbow flexed at 90° (Fig. 3). The upper extremities were placed in the weight-bearing condition with straps placed proximally on the forearms. The subject was asked to lean their body forward by flexing at the shoulders and straightening the elbows throughout the movement. For all conditions, verbal comments were made to keep the thumbs pointing upward, keep the pelvis in a neutral position, and maintain a neutral spine including the neck and head.

Prior to analysis of scapular motion, the sensors were securely attached to the subjects. Then, 3-D scapular and humeral kinematic data were collected for both the OKC and CKC conditions for all subjects. The testing order was randomized using computer-generated random numbers. Participants performed three repetitions of full

**Fig. 1.** Set-up for testing and sensor placement.

overhead arm elevation using the wooden frame as a guide, at a speed matching the beat of a metronome set at 60 beats per minute, using 3 s for elevation. All tests were performed in a single session; therefore, the sensors remained attached to the participants throughout testing.

### 2.4. Data analysis

Scapular rotations were represented using the y–x′–z′′ sequence, in which the first rotation defined the amount of internal–external rotation, second upward–downward rotation, and last anterior–posterior tilt. Humeral rotations were represented using the y–x′–y′′ sequence of humerothoracic elevation, in which the first rotation defined the plane of elevation, the second defined the amount of humerothoracic elevation, and the third defined the amount of axial rotation. Data for scapular orientation at 30°, 45°, 60°, 90°, and 120° of humerothoracic elevation were obtained for each repetition. The scapular orientation values at each humerothoracic elevation angle for each movement were then averaged across the three repetitions.

To be able to analyze scapular symmetry between dominant and nondominant shoulders or painful and non-painful shoulders obtained during OKC and CKC movements, the method suggested by Zifchock et al. (2008) was used to define symmetry angle (SA). This method is reported as an effective quantification of asymmetry for gait analysis and recommended preferably over the symmetry index, which is prone to normalization problems. The SA is a measure related to the angle formed when a right-side (dominant or involved shoulder) value is plotted against a left-side (nondominant or non-involved shoulder) value: (*Xright, Xleft*). The SA values were calculated from the data for each scapular kinematics variable identified previously at the same humerothoracic elevation angle using these formulae:

(1) If $(45^\circ - \arctan(Xleft/Xright)) < 90^\circ$, the following equation should be substituted

$$SA = \frac{\left(45^\circ - \arctan\left(\frac{Xleft}{Xright}\right)\right)}{90^\circ} \times 100\%$$

(2) If $(45^\circ - \arctan(Xleft/Xright)) > 90^\circ$, the following equation should be substituted

$$SA = \frac{\left(45^\circ - \arctan\left(\frac{Xleft}{Xright}\right) - 180^\circ\right)}{90^\circ} \times 100\%$$

**Fig. 2.** Open kinetic chain movement performed as shoulder flexion.

**Fig. 3.** Closed kinetic chain movement performed as forward leaning with slings.

The SA value of 0% indicates perfect symmetry, while 100% indicates that the two values are equal and opposite in magnitude.

*2.5. Statistical analysis*

Statistical analysis of kinematic data obtained from the involved shoulder of the symptomatic subjects and dominant shoulder of the asymptomatic subjects was performed using three separate 2 × 5, two-way, repeated-measures analysis of variance, with the factors of condition (OKC versus CKC) and humerothoracic elevation angle (30°, 45°, 60°, 90°, 120°). The Greenhouse–Geisser correction was used to adjust the degrees of freedom when the sphericity assumption was violated. When a significant interaction term was present, pairwise comparisons between conditions at each elevation angle were evaluated. When the interaction term was not significant, the main effect for loading was evaluated. Statistical analysis of SA was performed using a paired-samples Student's *t*-test to compare data obtained from each OKC and CKC movement recording at the same humerothoracic elevation angle for asymptomatic and symptomatic subjects separately. SPSS 20.0 was used for statistical tests, and the significance level was set at 0.05.

## 3. Results

For the dominant shoulder of asymptomatic subjects and involved shoulder of symptomatic subjects, scapular kinematics while performing shoulder elevation in OKC and CKC are illustrated in Figs. 4 and 5 for internal/external rotation, in Figs. 6 and 7 for upward/downward rotation, and in Figs. 8 and 9 for anterior/posterior tilt. In general, although some variations were observed, the scapula moved toward internal rotation, upward rotation, and posterior tilt during shoulder elevation for all conditions (Figs. 4–9).

*3.1. Scapular rotations*

*3.1.1. Asymptomatic subjects*

There was a statistically significant condition-by-angle interaction for scapular internal-external rotation ($F_{1.6,46.5}=3.67$, $p=0.04$).

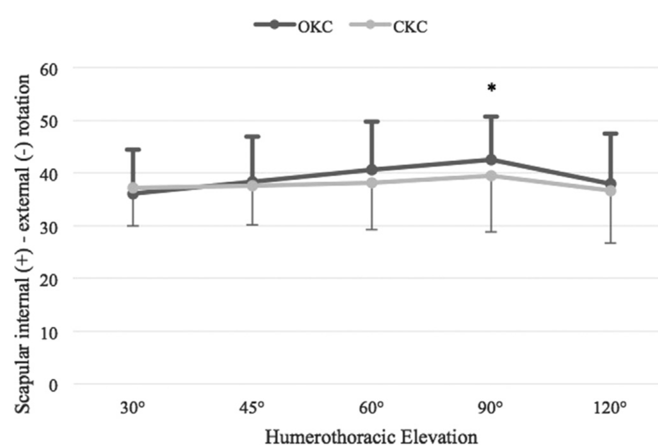


**Fig. 4.** Scapular internal–external rotation during open kinetic chain (OKC) and closed kinetic chain (CKC) shoulder elevation in asymptomatic shoulders. *Significant difference between movement conditions at this angle ($p<.05$).

Pairwise comparisons indicated that the scapula was more externally rotated at 90° ($p=0.03$; mean difference, 3.1°) humerothoracic elevation during CKC movement (Fig. 4). There was a statistically significant condition-by-angle interaction for scapular upward–downward rotation ($F_{2.08,60.4}=6.56$, $p=0.002$). Pairwise comparisons indicated that the scapula was more upwardly rotated at 90° ($p=0.002$; mean difference, 6.8°) and at 120° ($p=0.001$; mean difference, 8°) humerothoracic elevation during CKC movement (Fig. 6). There was also a statistically significant condition-by-angle interaction for scapular anterior–posterior tilt ($F_{1.4,40.7}=7.24$, $p=0.005$). Pairwise comparisons indicated that the scapula was more anteriorly tilted at 45° ($p=0.02$;

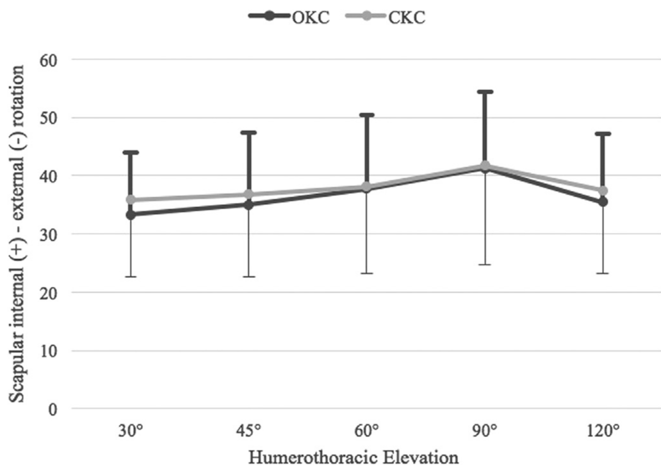


**Fig. 5.** Scapular internal-external rotation during open kinetic chain (OKC) and closed kinetic chain (CKC) shoulder elevation in symptomatic shoulders. *Significant difference between movement conditions at this angle ($p<.05$).

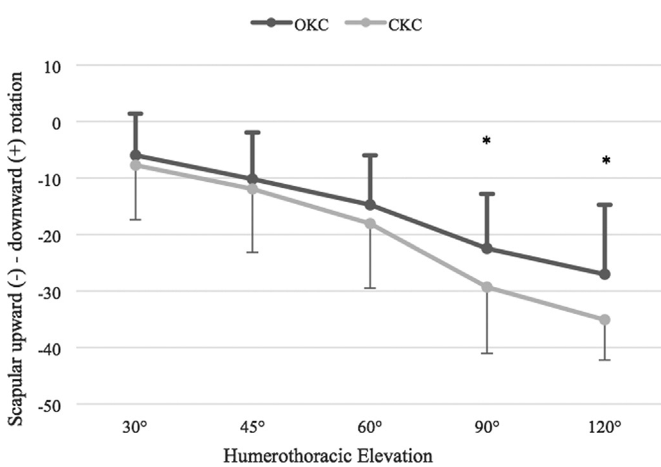


**Fig. 6.** Scapular upward–downward rotation during open kinetic chain (OKC) and closed kinetic chain (CKC) shoulder elevation in asymptomatic shoulders. *Significant difference between movement conditions at this angle ($p<.05$).

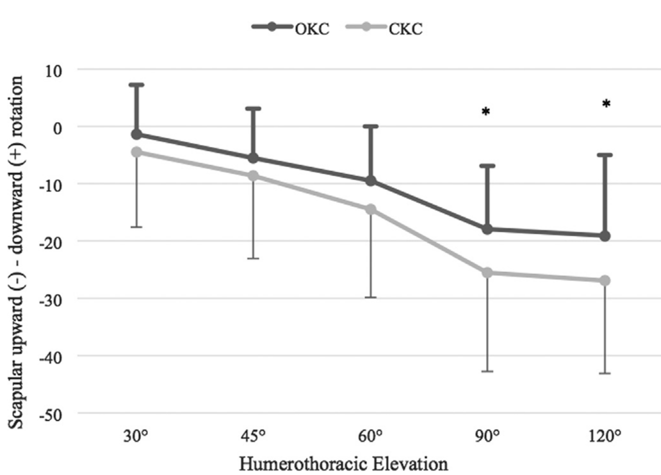


**Fig. 7.** Scapular upward–downward rotation during open kinetic chain (OKC) and closed kinetic chain (CKC) shoulder elevation in symptomatic shoulders.

mean difference, 1.8°), at 60° ($p=0.01$; mean difference, 1.9°), at 90° ($p=0.006$; mean difference, 4.7°), and at 120° ($p=0.002$; mean difference, 6.7°) humerothoracic elevation during CKC movement (Fig. 8).

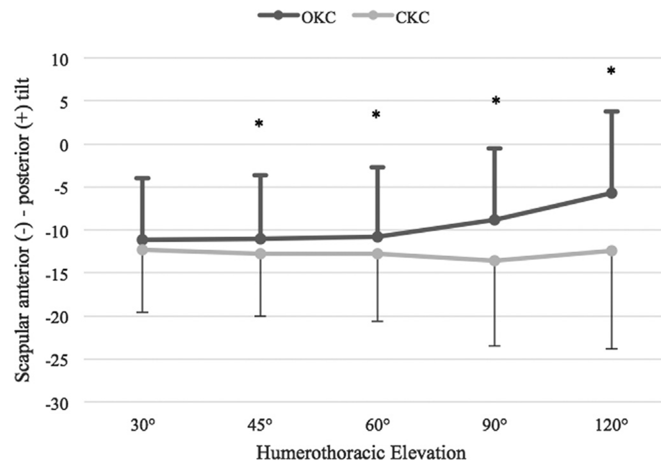


**Fig. 8.** Scapular anterior–posterior tilt during open kinetic chain (OKC) and closed kinetic chain (CKC) shoulder elevation in asymptomatic shoulders. *Significant difference between movement conditions at this angle ($p<.05$).

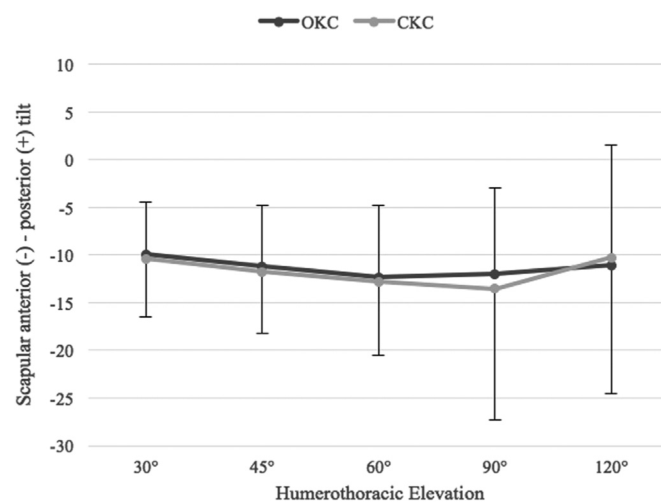


**Fig. 9.** Scapular anterior–posterior tilt during open kinetic chain (OKC) and closed kinetic chain (CKC) shoulder elevation in symptomatic shoulders.

### 3.1.2. Symptomatic subjects

There was no statistically significant condition-by-angle interaction ($F_{1.75,33.2}=0.55$, $p=0.55$) or main effect of condition ($F_{1,19}=0.72$, $p=0.40$) for scapular internal–external rotation (Fig. 5). There was a statistically significant condition-by-angle interaction for scapular upward–downward rotation ($F_{1.9,37.7}=4.61$, $p=0.01$). Pairwise comparisons indicated that the scapula was more upwardly rotated at 90° ($p=0.01$; mean difference, 7.6°) and at 120° ($p=0.004$; mean difference, 7.9°) humerothoracic elevation during CKC movement (Fig. 7). There was no statistically significant condition-by-angle interaction ($F_{1.8,35.2}=0.42$, $p=0.64$) or main effect of condition ($F_{1,19}=0.12$, $p=0.72$) for scapular anterior–posterior tilt (Fig. 9).

## 3.2. Symmetry angle

### 3.2.1. Asymptomatic subjects

Comparisons between OKC and CKC conditions at each angle of humerothoracic elevation indicated that the scapular anterior–posterior tilt was more symmetrical between dominant and non-dominant shoulders with CKC condition at 90° of humerothoracic elevation ($p=0.03$) and the scapular upward–downward rotation was more symmetrical in the CKC condition at 120° of humerothoracic elevation ($p=0.02$, Table 2).

**Table 2**
Comparison of symmetry angle for scapular kinematics during open kinetic chain (OKC) and closed kinetic chain (CKC) movements in asymptomatic subjects.

| Humerothoracic elevation | | Internal–External rotation | | Upward–Downward rotation | | Anterior–Posterior tilt | |
|---|---|---|---|---|---|---|---|
| | | Mean | (SD) | Mean | (SD) | Mean | (SD) |
| 30° | OKC | 5.54 | (4.01) | 32.41 | (22.36) | 15.63 | (10.85) |
| | CKC | 5.90 | (4.92) | 32.60 | (18.19) | 15.26 | (15.57) |
| | *p* | *0.74* | | *0.97* | | *0.91* | |
| 45° | OKC | 5.03 | (4.31) | 23.87 | (17.13) | 15.65 | (10.92) |
| | CKC | 6.31 | (4.90) | 26.21 | (20.34) | 19.75 | (21.09) |
| | *p* | *0.29* | | *0.66* | | *0.29* | |
| 60° | OKC | 4.89 | (4.34) | 15.48 | (13.17) | 19.29 | (13.25) |
| | CKC | 8.20 | (9.29) | 19.13 | (13.83) | 21.73 | (23.59) |
| | *p* | *0.07* | | *0.32* | | *0.56* | |
| 90° | OKC | 6.41 | (4.30) | 8.48 | (6.66) | 34.98 | (30.06) |
| | CKC | 8.07 | (6.19) | 13.28 | (19.89) | 21.73 | (23.59) |
| | *p* | *0.19* | | *0.23* | | *0.03** | |
| 120° | OKC | 9.81 | (7.64) | 12.25 | (13.53) | 29.38 | (26.61) |
| | CKC | 9.30 | (8.32) | 6.65 | (5.14) | 22.74 | (20.93) |
| | *p* | *0.82* | | *0.02** | | *0.30* | |

SD: Standard deviation.
Symmetry angle represented in percentage.
* Significant statistical difference based on comparisons.

**Table 3**
Comparison of symmetry angle for scapular kinematics during open kinetic chain (OKC) and closed kinetic chain (CKC) movements in symptomatic subjects.

| Humerothoracic Elevation | | Internal–External rotation | | Upward–Downward rotation | | Anterior–Posterior tilt | |
|---|---|---|---|---|---|---|---|
| | | Mean | (SD) | Mean | (SD) | Mean | (SD) |
| 30° | OKC | 8.02 | (10.48) | 33.04 | (27.57) | 17.38 | (13.78) |
| | CKC | 10.65 | (10.96) | 40.34 | (25.93) | 9.31 | (13.08) |
| | *p* | *0.39* | | *0.50* | | *0.08* | |
| 45° | OKC | 8.03 | (11.89) | 37.13 | (30.21) | 15.75 | (14.78) |
| | CKC | 10.90 | (12.03) | 44.30 | (35.23) | 15.55 | (23.69) |
| | *p* | *0.41* | | *0.42* | | *0.97* | |
| 60° | OKC | 7.45 | (11.38) | 30.73 | (30.41) | 18.56 | (16.86) |
| | CKC | 10.81 | (12.24) | 32.13 | (32.27) | 16.95 | (24.44) |
| | *p* | *0.35* | | *0.84* | | *0.76* | |
| 90° | OKC | 8.98 | (10.13) | 15.20 | (16.14) | 29.05 | (26.57) |
| | CKC | 12.37 | (12.80) | 17.66 | (24.69) | 16.95 | (24.44) |
| | *p* | *0.29* | | *0.69* | | *0.04** | |
| 120° | OKC | 12.83 | (10.68) | 18.49 | (15.08) | 32.08 | (26.54) |
| | CKC | 13.34 | (13.91) | 16.00 | (20.79) | 26.19 | (27.42) |
| | *p* | *0.89* | | *0.50* | | *0.54* | |

SD: Standard deviation.
Symmetry angle represented in percentage.
* Significant statistical difference based on comparisons.

### 3.2.2. *Symptomatic subjects*

Comparisons between OKC and CKC conditions at each angle of humerothoracic elevation indicated that the scapular anterior–posterior tilt was more symmetrical between involved and non-involved shoulders in the CKC condition at 90° of humerothoracic elevation ($p=0.04$, Table 3).

## 4. Discussion

The findings of the study indicated that 3-D scapular kinematics during OKC shoulder elevation differed from those during CKC movements. In general, the scapula was more externally rotated, upwardly rotated, and anteriorly tilted for asymptomatic shoulders, and more upwardly rotated for symptomatic shoulders during CKC shoulder elevation performed with slings.

When OKC and CKC movements compared, the magnitude of the difference in scapular upward rotation (up to 8°) reached the minimal detectable change value for both asymptomatic and symptomatic groups. Especially, increased upward rotation of the scapula at 90° and 120° of humeral elevation during CKC can be interpreted as an increased scapular contribution to total shoulder complex motion for all subjects. For asymptomatic shoulders, the magnitude of the difference in scapular external rotation and anterior tilt was relatively small and could not reach the minimal detectable change value; however, it was still more than the previously measured kinematic differences demonstrated between healthy and symptomatic individuals (Borstad and Ludewig, 2002). When considering the normal motion of the scapula during shoulder elevation, scapular external rotation was presumed to have less potential risk of reducing the subacromial space, especially for higher elevation ranges; in contrast, increased scapular anterior tilt was presumed to have a contributory effect on subacromial or internal impingement and lesser inferior and anterior stability of the glenohumeral joint (Ludewig and Reynolds, 2009). Therefore, possible adaptations to training in the CKC position in scapular kinematics and its relation to clinical symptoms should be further investigated.

CKC movement resulted in more symmetrical scapular motion, especially at 90° and 120° of shoulder elevation, which requires more muscular support to maintain shoulder stability and mobility (Wuelker et al., 1998). Dillman et al. (1994) suggested that CKC exercise may establish early proximal stability of the joint, providing a stable base for the upper extremity to function. Previously, Tucker et al. (2010) investigated the electromyographic activity of scapular muscles during cuff-link and standard push-up exercises. Furthermore, he found that weight-bearing positions caused changes in neuromuscular control strategies as a result of axial loading and increased compressive forces around the joint complex. Similar to the CKC movement tested in this study, Hardwick et al. (2006) showed increased serratus anterior muscle activation during the CKC wall slide exercise. Axial loading may result in changes in force couple activation and may lead to alterations in scapular kinematics and symmetry.

In this study, CKC elevation performed with a novel training device providing weight-bearing positions and incorporating the kinetic chain and Redcord slings are often utilized as CKC exercises (Chang et al., 2014; De Mey et al., 2014; Prokopy et al., 2008). The rope and sling system ensures axially loaded movement that allows the distal segment to move while the subject maintains an axial load through the shoulder complex. Because the distal segment moves deliberately, the tested movement may not fit strictly to the some of the definitions of CKC exercise. However, a potential advantage of utilizing the rope and sling system during humeral elevation is that execution of the body requires elevation of the humerus relative to the thorax starting from the resting position to full elevation to assess dynamic shoulder kinematics. Moreover, slings can create an unstable environment that may supply more proprioceptive input for movement control (Kirkesola, 2009;

Tsauo et al., 2008). In addition, loading magnitude and force direction differences should also have been considered as other factors affecting neuromuscular control strategies across OKC and CKC when interpreting the results of the study. During the OKC movement, shoulder flexors present a concentric contraction, whereas shoulder extensors act eccentrically during the CKC movement. During CKC movement, potentially increased agonist–antagonist cocontraction may also affect muscular activation status. The specificity of the load and muscular response to the movement that was selected for investigation may have reduced the generalizability of our results. However, we believe that our detailed description of scapular kinematics in both asymptomatic and symptomatic shoulders provides important baseline information to guide future research.

The findings of this study are limited to the asymptomatic young population and subjects with mild shoulder pain. However, the pain experience for unilateral shoulder injuries results in altered neuromuscular control, which reveals delayed activation onset of the middle and lower trapezius bilaterally (Cools et al., 2003). Considering kinematic alternations related to shoulder pathologies and maintaining scapular mobility and stability is often accepted as a critical component of shoulder rehabilitation (Kibler et al., 2013; Ludewig and Reynolds, 2009). Thus, patients who have painful active shoulder motion may benefit from CKC exercises performed with slings because of obtained changes in kinematics and more symmetrical scapular movements.

In conclusion, CKC movement affected scapular kinematics, especially through increased upward rotation for both symptomatic and asymptomatic shoulders similarly. Furthermore, CKC movement revealed more symmetrical scapular motion, especially for the humerothoracic elevation above 90°. Thus, CKC exercises can be applied securely for both training purposes in asymptomatic populations and treatment purposes in the early rehabilitation of patients who have shoulder impingement syndrome.

## Conflict of interest statement

The authors certify that they have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the article. No foundation funds were received in support of this work. No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

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