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Differences in scapular kinematics and scapulohumeral rhythm during elevation and lowering of the arm between typical children and healthy adults

Fernanda A.P. Habechian [a], Giovanna G. Fornasari [a], Luciane S. Sacramento [b], Paula R. Camargo [a,b,*]

[a] Methodist University of Piracicaba, Piracicaba, SP, Brazil
[b] Federal University of São Carlos, São Carlos, SP, Brazil

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ABSTRACT

Scapular kinematics in healthy adults is well described in the literature but little is known on typical children. This study aimed to compare the three-dimensional (3-D) scapular kinematics and scapulohumeral rhythm during the elevation and lowering of the arm in the scapular plane in typical children and healthy adults. Twenty-six healthy adults (35.34 ± 11.65 years, 1.70 ± 0.10 m, 70.00 ± 12.30 kg) and 33 typical children (9.12 ± 1.51 years, 1.40 ± 0.10 m, 35.40 ± 10.45 kg) participated in this study. 3-D scapular kinematics were obtained using an electromagnetic tracking device. The subjects were asked to elevate and lower their arm in the scapular plane. Children showed less scapular protraction compared to adults at 120° during arm elevation, more anterior tilt than adults in the elevation and also at 60°, 90° and 120° during lowering of the arm. Children also showed higher scapulohumeral rhythm during lowering of the arm compared to adults from 90° to 60°. It was also found a low to little correlation between scapular position and age. The study showed small but significant differences in scapular kinematics and scapulohumeral rhythm between children and adults. These results can help clinicians to improve diagnosis and treatment protocols directed to children with dysfunction, as reference values on scapular kinematics in healthy children are also provided in this study.

1. Introduction

Position and control of the scapula on the thorax play an important role on normal function of the shoulder as it provides stable base for humeral motion (Kibler and McMullen, 2003). In healthy adults, it is well described that the scapula should laterally rotate and posteriorly tilt during elevation of the arm (Ludewig et al., 2009). Scapular protraction is less consistent during arm elevation, however it is accepted that some retraction will occur near end range of humeral elevation (McClure et al., 2001; Ludewig et al., 2009).

The literature has supported that alterations in scapular kinematics are associated with shoulder dysfunctions (Phadke et al., 2009; Ludewig and Braman, 2010). In the past, shoulder dysfunctions were mostly described in adults. The increasing number of children and adolescents athletes, especially in throwing sports, has contributed to increase the incidence of shoulder injuries in the pediatric population (Paterson and Waters, 2000; Leonard and Hutchinson, 2010; Cools et al., 2010; Eisner et al., 2013). However, little is known about scapular kinematics in children.

Only one study was found comparing the three-dimensional (3-D) scapular kinematics between children and adults during elevation of the arm (Dayanidhi et al., 2005). The authors described some differences in scapular kinematics pattern between the two groups and concluded that children have more contribution from the scapulothoracic joint than adults. This study only assessed scapular kinematics during elevation of the arm. However, lowering of the arm is also important to be analyzed once it is usually in this phase that scapular dyskinesia is observed in a clinical screening (Warner et al., 1992; Boublik and Hawkins, 1993; Kibler, 1998). No studies were found about lowering of the arm in children and there are few done in adults (Borstad and Ludewig, 2002; Ludewig et al., 2009; Matsuki et al., 2011; McClure et al., 2001).

Thereby, investigations on scapular kinematics in children are warranted as knowing the typical motion in this population is the basis for the understanding of motor abnormalities that may be associated with shoulder dysfunctions. This can help clinicians to decide on more adequate exercise approaches for rehabilitation in children with upper extremity disorders such as rotator cuff dysfunctions, and with neurological disorders such as cerebral

* Corresponding author. Address: Universidade Federal de São Carlos, Rod. Washington Luis, km 235, CEP: 13565-905 São Carlos, SP, Brazil. Tel.: +55 16 3306 6696.

E-mail address: paularezendecamargo@gmail.com (P.R. Camargo).

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palsy, brachial plexus injury and spinal cord injury (Mosqueda et al., 2004; Coluccini et al., 2007; Jaspers et al., 2011).

The hypothesis of this study is that adults and children present differences in scapular kinematics in both elevation and lowering of the arm. The aim was to compare the 3-D scapular kinematics and scapulohumeral rhythm during elevation and lowering of the arm in the scapular plane in typical children and healthy adults.

2. Methods

2.1. Subjects

This is a cross-sectional study with non-probabilistic sampling and by convenience. Twenty-six adults and 33 typical children participated in the study. The descriptive data of the participants are presented on Table 1. The study included individuals who had no history of shoulder or cervical dysfunction and who had range of motion for shoulder elevation next to 150° as evaluated by visual observation. The range of age accepted was between 18 and 55 years for adults and 6–12 years for children.

Subjects were excluded if any of the following was found: unilaterally dominant upper-extremity-sport/labor subjects; cervical pain; history of surgical stabilization or repair of the rotator cuff; positive impingement or instability tests; fracture history in the clavicle, scapula or humerus; systemic diseases involving the joints; cognitive deficits preventing the understanding of verbal commands; brachial plexus injury; transpore tape allergy; children with body mass index (BMI) higher than 1 standard deviation according to the growth reference for BMI in score z for youth and adolescents of the World Health Organization (De Onis et al., 2007) and adults with BMI > 28 kg/m^2 (the amount of subcutaneous tissue can compromise the quality of the motion data as surface sensors were used to track the bones). Children were also excluded in case of delayed motor development based on parentś report.

The study was approved by the research ethical committee of the University. Adults and children and their parents received verbal and written explanation of the objectives and methodology of the study and who agreed to participate signed a consent form.

2.2. Instrumentation

To evaluate 3-D kinematics, the capture and analysis were performed using the electromagnetic tracking device Flock of Birds® (miniBird®) integrated with MotionMonitor™ software that is used to collect data with a sampling frequency of 100 Hz. In a metal free environment up to a 76 cm distance from the transmitter the root mean square accuracy of the system is 0.5° for orientation and 0.18 cm for position, as reported by the manufacturer.

2.3. Procedures

The dominant arm was evaluated in all children to make the test easier for them. Dominance was determined by asking them which hand is used to draw or write. The adults had the tested side randomly chosen because it is already shown in the literature that there are no significant differences in scapular kinematics between both sides in healthy adults (Yoshizaki et al., 2009).

The surface electromagnetic sensors were attached with double sided tape to the sternum, the acromion of the scapula and a thermoplastic cuff attached to the distal humerus to track humeral motion. The subject stood with the arms relaxed at the side in a neutral position with the transmitter directly behind the shoulder tested while bony landmarks on the thorax, scapula and humerus were palpated and digitized with a stylus with known offsets to allow transformation of the sensor data to local anatomically based coordinate systems. Local coordinate systems were established for the trunk, clavicle, scapula and humerus using the digitized landmarks following the International Society of Biomechanics recommended protocol (Wu et al., 2005). The *z*-axis pointed laterally, the *x*-axis anteriorly and the *y*-axis superiorly.

Kinematic data collection was done with the subjects in a relaxed standing position. Subjects were asked to maintain light fingertip contact with a flat planar surface to keep positioning of the arm in the scapular plane (45° anterior to the coronal plane). They were also instructed to keep their hand with their thumb pointing toward the ceiling. Three repetitions were performed. Subjects were asked to elevate their arm from the rest position through their full range of motion at a speed such that it took around 3 s to elevate their arm and 3 s to lower it.

2.4. Data reduction

MATLAB software was used to reduce the data. Scapular kinematics was analyzed at 30°, 60°, 90° and 120° of elevation and lowering of the arm. The *YXZ* sequence was used to describe scapular motions relative to the trunk. For the scapula, the rotations were described in the order of protraction/retraction, lateral/medial rotation and anterior/posterior tilt (Wu et al., 2005). The humeral position with reference to the trunk was determined using the $Y'XY''$ sequence. The first rotation defines the plane of elevation, the second defines the humeral elevation angle, and the third defines internal/external rotation. The humeral position with reference to the scapula was determined using the *XZY* sequence as recommended by Phadke et al. (2011). The first rotation defines glenohumeral elevation, the second defines the plane of glenohumeral elevation, and the third defines internal/external rotation.

For scapulohumeral rhythm, the ratio of the glenohumeral elevation relative to lateral rotation of the scapula was determined by calculating the slope of the linear regression line using the lateral rotation of the scapula as *X* value and the glenohumeral elevation as *Y* value as proposed by Braman et al. (2009). The ratio was calculated from 30° to 120° of humerothoracic elevation, from 120° to 30° of humerothoracic lowering, and at 30° increments for elevation (30°–60°, 60°–90°, 90°–120°) and lowering (120°–90°, 90°–60°, 60°–30°) of the arm.

2.5. Statistical analysis

The data were averaged over the three repetitions of elevation and lowering of the arm and analyzed using the NCSS statistical package (NCSS, Kaysville, UT). The Shapiro–Wilk test was used to check the normality of the data. For scapular protraction, lateral rotation and tilt, a 2-way mixed ANOVA was conducted for each phase (elevation and lowering), in separate, with humeral angle (30°, 60°, 90° and 120°) as within factor and group (children and adults) as between factor. The primary interest was to check interaction of group × humeral angle and secondarily the main effect of group. The Bonferroni test for post hoc analysis was used when necessary. For scapulohumeral rhythm, the same statistical procedure was followed but interval (30°–60°, 60°–90°, 90°–120°,

Table 1
Characteristics of the participants of the study.

	Adults (n = 26)	Children (n = 33)
Sex	14 females; 12 males	15 females; 18 males
Age (years)	35.34 ± 11.65	9.12 ± 1.51
Height (m)	1.70 ± 0.10	1.40 ± 0.10
Weight (kg)	70.00 ± 12.30	35.40 ± 10.45

Results are mean and standard deviation.

30°–120°, 120°–90°, 90°–60°, 60°–30°, 30°–120°) was used instead of humeral angle. A p value of less than 0.05 was considered significant.

The relationship between scapular position and age was assessed by performing linear regressions at each humeral angle during elevation and lowering of the arm for each variable (scapular protraction, lateral rotation and tilt) in separate. Age was used as independent factor and scapular position as outcome. The coefficient of determination was assessed by calculating the square of the correlation coefficient.

3. Results

3.1. Scapular kinematics and scapulohumeral rhythm

For scapular protraction, children showed less protraction at 120° humeral angle during elevation of the arm when compared to adults ($F = 5.12$; $p = 0.002$). There was no significant interaction between group and humeral angle ($F = 1.49$; $p = 0.21$), nor was there significant main effect of group ($F = 0.50$; $p = 0.48$) during lowering of the arm. Fig. 1 shows the scapular protraction during elevation and lowering of the arm.

For scapular lateral rotation, there was no significant interaction between group and humeral angle ($F = 1.16$; $p = 0.32$, for elevation; $F = 1.06$; $p = 0.36$, for lowering), nor was there significant main effect of group ($F = 3.78$; $p = 0.056$, for elevation; $F = 0.35$; $p = 0.55$, for lowering) during elevation and lowering of the arm (Fig. 2). However, the children showed a tendency ($F = 3.78$; $p = 0.056$) to present less lateral rotation compared to adults.

For scapular tilt (Fig. 3), there was no significant interaction between group and humeral angle ($F = 1.82$; $p = 0.14$) during elevation of the arm, but there was a significant main effect of group with children presenting more anterior tilt when compared to adults ($F = 6.01$; $p = 0.01$). However, children showed more anterior tilt at 120°, 90° and 60° humeral angles during lowering of the arm when compared to adults ($F = 3.89$; $p = 0.01$) (Table 2).

For the scapulohumeral rhythm, there was no significant interaction between group and humeral angle ($F = 2.33$; $p = 0.13$), nor was there significant main effect of group ($F = 0.36$; $p = 0.54$) during elevation of the arm. There was significant interaction between group and interval ($F = 4.39$; $p = 0.04$) during lowering of the arm in which children showed increased scapulohumeral rhythm in the range of 90°–60° of lowering of the arm compared to adults ($F = 7.17$; $p = 0.01$). Table 3 shows the glenohumeral/scapulothoracic ratios during elevation and lowering of the arm for adults and children.

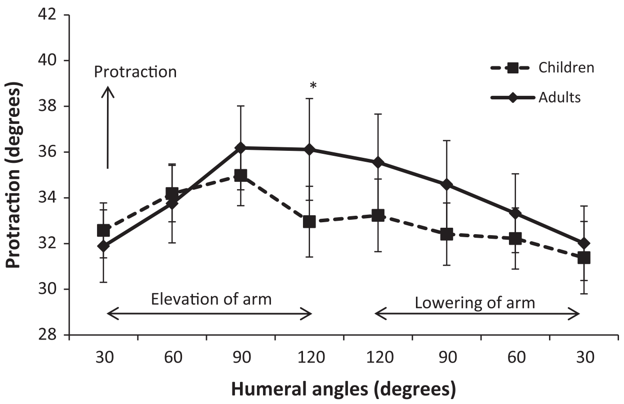

Fig. 1. Means of scapular protraction during elevation and lowering of the arm in the scapular plane in adults ($n = 26$) and children ($n = 33$). The error bars represent the standard error of the mean. *Significant difference ($p < 0.05$) between groups.

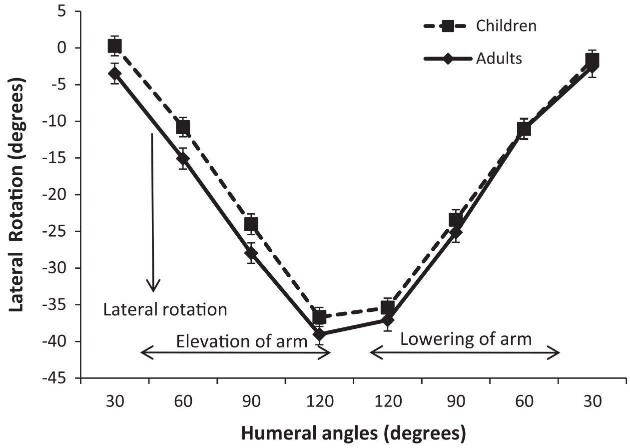

Fig. 2. Means of scapular lateral rotation during elevation and lowering of the arm in the scapular plane in adults ($n = 26$) and children ($n = 33$). The error bars represent the standard error of the mean.

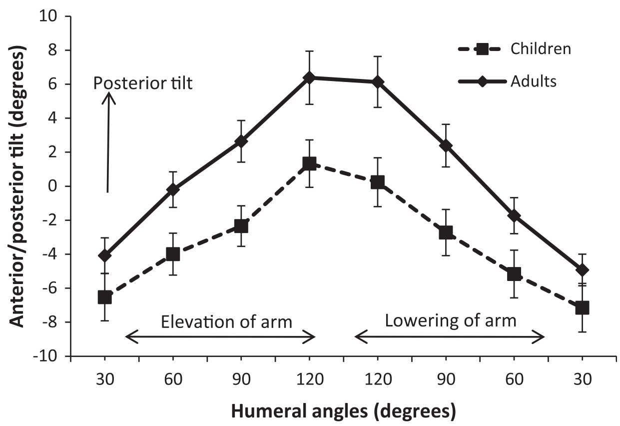

Fig. 3. Means of scapular anterior and posterior tilt during elevation and lowering of the arm in the scapular plane in adults ($n = 26$) and children ($n = 33$). The error bars represent the standard error of the mean.

Table 2
Interaction of group × humeral angle of the scapular tilt in healthy adults and typical children during elevation and lowering of the arm.

	Adults ($n = 26$)	Children ($n = 33$)
Elevation		
30°	−4.08 ± 1.04	−6.53 ± 1.39
60°	−0.20 ± 1.05	−4.00 ± 1.23
90°	2.63 ± 1.22	−2.35 ± 1.19
120°	6.37 ± 1.56	1.32 ± 1.39
Lowering		
120°	6.13 ± 1.50	0.23 ± 1.43*
90°	2.38 ± 1.25	−2.73 ± 1.35*
60°	−1.73 ± 1.06	−5.17 ± 1.40*
30°	−4.93 ± 0.93	−7.15 ± 1.43

Results are mean and standard error of the mean. Negative number indicates anterior tilt.
* Significant difference ($p < 0.05$) between groups.

3.2. Correlation and linear regression

Table 4 shows the relationships between scapular position and age in all testing positions of elevation and lowering of the arm. Low or little correlation was demonstrated to all scapular rotations (r values ranging from −0.30 to 0.40). The coefficient of determination (R^2) showed that only 0.03%–16% of the variability in the scapular kinematics can be attributed to age.

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Table 3
Scapulohumeral rhythm during elevation and lowering of the arm in the scapular plane in healthy adults and typical children.

	Adults ($n = 26$)	Children ($n = 33$)
Elevation		
30°–60°	1.64 ± 0.13	1.88 ± 0.11
60°–90°	1.44 ± 0.09	1.43 ± 0.08
90°–120°	1.99 ± 0.17	1.57 ± 0.15
30°–120°	1.52 ± 0.08	1.43 ± 0.07
Lowering		
120°–90°	1.78 ± 0.16	1.78 ± 0.15
90°–60°	1.21 ± 0.15	1.75 ± 0.13*
60°–30°	2.71 ± 0.23	2.59 ± 0.21
120°–30°	1.45 ± 0.10	1.67 ± 0.09

Results are mean and standard error of the mean.
* Significant difference ($p < 0.05$) between groups.

Table 4
Relationship between age and scapular kinematics in all testing positions of elevation and lowering of the arm.

	Elevation of the arm			Lowering of the arm		
	r	R^2	p	r	R^2	p
Protraction						
30°	−0.03	0.001	0.78	0.07	0.005	0.58
60°	−0.01	0.0003	0.90	0.09	0.01	0.49
90°	0.08	0.007	0.53	0.13	0.02	0.31
120°	0.13	0.02	0.31	0.09	0.008	0.49
Lateral rotation						
30°	−0.25	0.06	0.06	−0.09	0.01	0.46
60°	−0.30	0.09	0.02*	−0.02	0.001	0.84
90°	−0.31	0.10	0.01*	−0.18	0.03	0.17
120°	−0.27	0.08	0.03*	−0.24	0.06	0.06
Tilt						
30°	0.14	0.02	0.28	0.14	0.02	0.27
60°	0.30	0.09	0.02*	0.28	0.08	0.03*
90°	0.39	0.16	0.002*	0.40	0.16	0.001*
120°	0.32	0.11	0.01*	0.36	0.13	0.004*

r Indicates correlation. R^2 indicates coefficient of determination.
* Statistically significant ($p < 0.05$).

4. Discussion

To our knowledge this is the first study that compares scapular kinematics during both elevation and lowering of the arm between children and adults. In general, the scapula increased protraction and lateral rotation, and progressed from anterior to posterior tilt during elevation of the arm in both groups, and returned to the initial position during lowering of the arm. Despite of the similar scapular kinematics pattern, subtle differences were identified. As such, the findings of this study partially support the hypothesis that children and adults differ in scapular kinematics during elevation and lowering of the arm.

The lateral rotation was the most consistent motion of the scapula during elevation and lowering of the arm in both groups. It is the scapular motion of greatest range. Although the adults had tendency to present more lateral rotation than the children, significance was not reached. These findings are contrary to what was previously demonstrated by Dayanidhi et al. (2005) who identified children to have greater lateral rotation from 25° to 125° of humeral elevation in the scapular plane. The difference between both studies can be due to methodological issues. The present study used the posterolateral acromion, the root of the scapular spine and the inferior angle of the scapula to build the scapular local coordinate system, while Dayanidhi et al. (2005) used the acromiclavicular joint instead of the posterolateral acromion. Ludewig et al. (2010) have demonstrated that less lateral rotation is observed when the posterolateral acromion is digitized.

Analyzing the protraction of the scapula, children showed less protraction at 120° humeral angle during elevation of the arm when compared to adults. Observing Fig. 1, it can be noticed that children actually presented more retraction at 120° of arm elevation. This finding is in accordance with the literature that reports that some retraction of the scapula occurs near end range of motion (Borstad and Ludewig, 2002; Ludewig and Cook, 2002; McClure et al., 2001). The pattern described in this study is also similar to the pattern described by Lempereur et al. (2012) in typically developing children. However, the children evaluated by Dayanidhi et al. (2005) showed a retraction pattern earlier in the range of motion (beyond 60° of arm elevation). Despite of the aging influence, adults may also experience postural influences such as slouched posture or thoracic kyphosis, for example (Finley and Lee, 2003), which contribute for increased scapular protraction.

With regards to the scapular tilt, children showed more anterior tilt than adults during elevation of the arm and at 60°, 90° and 120° humeral angles during lowering of the arm. The scapula of the children remained mostly in anterior tilt during elevation of the arm, except at 120° humeral angle where it was slightly posteriorly tilted (1.32°). This pattern differs from the adults who reached 6.37° of posterior tilt at 120° humeral angle. Dayanidhi et al. (2005) reported a similar pattern of posterior tilt between children and adults, except for a small anterior tilt at the end of the range demonstrated by the children. Although we have not evaluated clavicular kinematics, increased clavicle elevation has been already demonstrated in children (Dayanidhi et al., 2005). This fact can contribute for the more anterior tilt found in our children as the clavicle elevation seems to contribute to 75% of anterior tilt of the scapula relative to the trunk (Ludewig and Braman, 2010). One might argue if the length of the clavicle could also contribute for a great deal of anterior tilt. In a cadaveric study, Matsumura et al. (2010) have demonstrated that scapular anterior tilt increased with 10% shortening of the clavicle when compared to a normal length clavicle. The length of the clavicle was not assessed in the current study, but the authors believe that its length can differ between children and adults with children presenting shorter clavicle contributing to more anterior tilt. Investigations should be done to verify if the clavicles are shorter in children and if it correlates with the increased anterior tilt.

The scapulothoracic muscles are very important for scapular stability. The serratus anterior contributes substantively to scapular posterior tilt. It is the only scapulothoracic muscle with the capability to both laterally rotate and posteriorly tilt the scapula on the thorax making its contribution to normal scapular kinematics very significant. Its line of action will directly approximate the scapula to the thorax, which can serve as a stable base (Phadke et al., 2009). As children have a distinct anatomy that is in continuous modification to improve their systems and also to adapt to their new environment (Schuenke et al., 2006), it is possible that the line of action of the scapulothoracic muscles might be different from the adults causing change in the scapular kinematics.

In the current investigation, higher scapulohumeral rhythm was seen in children from 90° to 60° of arm lowering. As the average of scapular lateral rotation was similar between children and adults, we believe this difference may be related to less contribution of the glenohumeral joint in adults during this interval of motion. Although muscular strengthening (Wang et al., 1999) as well as fatigue (McQuade et al., 1995) have been shown to influence the scapulohumeral rhythm, we are not able to explain the mechanism that may have lead to this behavior in our subjects due to the lack of literature on this topic and lack of muscle activity assessment in this study.

Low to little correlation was demonstrated between scapular position and age. Endo et al. (2004) have previously described the effects of aging on the shoulder analyzing antero-posterior

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radiography. The authors observed a decrease of posterior tilt and lateral rotation angle with aging. Direct comparisons cannot be done between the present study and the Endo et al. (2004) because of differences in methodology and study design. It is important to consider that the primary aim of this investigation was to compare the scapular kinematics between children and adults. As such, this is not the best design to determine about possible correlations on scapular position and age as a wide range of age would be necessary.

Considering that the skills to position and control the movements of the scapula are essential to the normal functioning of the upper limb (Jobe and Pink, 1993), the findings of this investigation provide new knowledge about scapular kinematics during elevation and lowering of the arm in children. Furthermore, due to the high mobility of the shoulder complex, it is highly susceptible to dysfunction and instability. The inability to control the scapula can usually contribute for development of shoulder pathologies (Kamkar et al., 1993). Thus, it is relevant to understand the scapular kinematics in typical children as an attempt to improve diagnostic and treatment protocols.

As this investigation brings reference values of scapular kinematics for healthy children, these results may help clinicians develop distinct treatment protocols for children and adults once children cannot be considered as miniature of the adults. This study may also provide knowledge for better rehabilitation programs for children with neurological problem, as for example, cerebral palsy, brachial plexus birth palsy and spinal cord injured children once proximal stabilization of the upper extremity is very important for them to perform functional activities. Children with upper extremity injuries such as rotator cuff tears and associated pathologies in shoulder due to their early engagement in sports (Tarkin et al., 2005; Leonard and Hutchinson, 2010; Eisner et al., 2013), especially the throwing, can also benefit from these findings.

The present study also has some limitations: (1) a large range of age in the adults group was considered; (2) scapular muscles activity was not measured; and (3) clavicular motion and length were not assessed. Further research should consider children and adults to perform elevation of the arm with a weight in hand as this condition may bring out greater differences between groups.

5. Conclusion

The findings of this study indicates that there is similarity in scapular kinematics pattern between children and adults during elevation and lowering of the arm, except for scapular protraction at 120° of humeral elevation where children present less protraction. Children also present more anterior tilt than adults. Reference values on scapular kinematics in healthy children are also provided in this study.

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Fernanda Assis Paes Habechian received her bachelor's degree and a Master in Physical Therapy from Universidade Metodista de Piracicaba (Brazil). She is currently a PhD student at Universidade Federal de São Carlos (Brazil). Her research interests are shoulder biomechanics in children and adolescents.

Giovanna Gurgel Fornasari is currently a Physical Therapy student at Universidade Metodista de Piracicaba (Brazil). Her research interests focus on shoulder biomechanics.

Luciane da Silva Sacramento received her bachelor's degree in Physical Therapy from Faculdade de Alagoas (Brazil). She is currently a Master student at Universidade Federal de São Carlos (Brazil). Her research interest is shoulder pain.

Paula Rezende Camargo received her bachelor's degree,a Master and a PhD in Physical Therapy from Universidade Federal de São Carlos (Brazil). She is currently Professor and Researcher in the Physical Therapy Graduate Program at Universidade Federal de São Carlos. Her research interests are shoulder biomechanics and evidence-based rehabilitation for shoulder dysfunctions

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