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Strength and activity of the protractor and retractor muscles of the asymptomatic dyskinetic scapula

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Abstract

The role of scapular dyskinesis as a risk factor of shoulder injury has been largely discussed. However, most studies have focused on symptomatic patients and less is known on the asymptomatic dyskinetic scapula. Removing the confounding effects of the pathologies could contribute to better characterize the scapula dyskinesis. As muscle properties (strength, fatigue, nerve injury …) have been identified as causative factors of scapular dyskinesis, this study focuses specifically on characterizing the protractor and retractor muscles of the dyskinetic scapula. Thirteen asymptomatic dyskinetic volunteers were compared to eleven asymptomatic non-dyskinetic control volunteers. Muscle characteristics were evaluated in terms of maximal strength, fatigue resistance and electromyographic activity during a functional closed-chained task. The results did not identify kinematic or muscle activity significant differences between the dyskinetic and the control group even in fatigue conditions. However, the results demonstrated that protractors vs. retractors fatigue resistance ratios were imbalanced (<0.8) in the dyskinetic group and significantly lower than in the non-dyskinetic one. Our study suggests that that strength imbalances are not necessarily related to the presence of pain at the shoulder joint. These results demonstrated the importance to complete the clinical assessments of the scapula with strength evaluations even for asymptomatic sport practitioners.

Introduction

The shoulder is one of the most mobile and complex joints of the human body (Inman et al., 1944). Repeated overhead high loads during sports activities may lead to pain or injuries of different types including shoulder impingement syndromes, tendinopathies, glenohumeral instabilities (Lin et al., 2018; Noreski & Cohen, 2015; Tooth, Gofflot, et al., 2020). Scapular dyskinesis relates to impaired statics and/or kinematics of the scapula (Kibler et al., 2012). There are discussions in the literature on whether dyskinesis should be considered as a risk factor of pain and/or injury at the shoulder joint. These discussion have been summarized in several meta-analyses. First, Hickey et al. (Hickey et al., 2018) meta-analysis have reported that the risk to develop shoulder pain is increased by 43% in asymptomatic overhead athletes over a period of 9 to 24 months in comparison to a non-dyskinetic group. More recently, another meta-analysis (Hogan et al., 2021) including more studies did not report a direct association between scapular dyskinesis and the development of shoulder injuries. If the literature does not identify a relationship between scapular dyskinesis on it own and shoulder injuries, the implications of a scapular dyskinesis remain unclear. If some authors have suggested that scapular dyskinesis may be related to the natural kinematic variability (McQuade et al., 2016), some others hypothesized that scapular dyskinesis may conditionally contribute to increasing the risk induce by other factors such as the work load (Møller et al., 2017). Other authors have identified reduced muscle strength in dyskinetic populations (Martens et al., 2023), which may further open the discussion to performance in dyskinetic populations.

Kibler (Kibler, 2006) has identified, among the causative factors for scapular dyskinesis, alterations of the muscle properties including inflexibility, weakness, fatigue, altered activation pattern and nerve injury. While the internal and external shoulder rotators have been studied in several papers (Forthomme et al., 2011; Moraes et al., 2008; Tooth et al., 2022) less has been done concerning the protractor and retractor muscles of the shoulder despite their importance in the stabilization of the scapula (Ben Kibler, 1998). Cools et al. (Cools et al., 2005) have investigated the scapular muscle performance (i.e., protractors and retractors) in overhead athletes with and without impingement symptoms but did not evaluate the dyskinesis. Borstad et al. (Borstad et al., 2009) evaluated the effect of scapular muscle fatigue on the scapular kinematics but only on healthy volunteers without dyskinesis. Asymptomatic (no pain) dyskinetic athletes have therefore been less studied. Understanding the specificities of asymptomatic dyskinetic athletes could contribute to distinguishing alterations related to dyskinesis in opposition to alterations related to other (confounding) factors such as pain. This knowledge could contribute to better understand the impact of dyskinesis on the shoulder function. Injury prevention as well as performance at the shoulder joint may benefit from such knowledge.

Concerning the dynamic stability of the scapula, studies have suggested that scapular dyskinesis may be more apparent when increased loads are used (McClure et al., 2009) as more stabilization is required and that scapula rhythm may be altered in fatigue conditions (Zago et al., 2020). Closed chained exercises, such as push-up plus tasks, are good candidates for a functional evaluation of the scapular stabilizers as they can induce majored loads with respect to opened chain exercises. The "plus" of the task refers to the isolated protraction of the scapula. Ludewig et al. described push-up plus tasks (Ludewig et al., 2004) which significantly recruit the serratus anterior muscle, which is one important scapular stabilizer. Furthermore, Borstad et al. (Borstad et al., 2009) demonstrated that an isometric push-up plus task was able to fatigue serratus anterior, infraspinatus, lower trapezius muscles and, to a lower extent, the upper trapezius muscle. Horsak et al. (Horsak et al., 2017) demonstrated that the "plus" phase was sufficient to activate serratus anterior (approximately 40% of maximal isometric voluntary activation). Furthermore, Push-up plus tasks can easily be repeated in order to induce fatigue. Push-up plus exercises seems therefore to be relevant tasks to study the capacity of volunteers to stabilize their scapula.

The objective of this study was to provide an evaluation of the protractor and retractor muscles of the asymptomatic dyskinetic scapula including muscle strength, fatigue resistance and activation during a closed chain functional task. The scapular kinematics will also be evaluated. We hypothesize that the asymptomatic dyskinetic group will present less muscular strength and increased imbalances as suggested in (Martens et al., 2023) concerning strength.

Material and methods

Participants

Twenty-five male volunteers were recruited with fourteen in the dyskinetic asymptomatic (DS-A) and eleven in the healthy control (HC) groups. The volunteers practiced various sports including overhead sports (waterpolo, hockey, tennis, volley, swimming, athletism, crossfit, judo, football, boxing) between two and ten hours of sport per week. None of the volunteers had a history of surgery or injury in the last six months at their upper limbs. The volunteers should also be negative to impingement syndrome (Neer's, Hawkins', and Yocum's tests) and tendinous (Jobe's test, Patte's test, liftoff test, and palm-up test) tests (Rockwood et al., 2004). For the dyskinetic group, only participants with unilateral dyskinesis were included. For sports with a dominance preference (such as tennis), the dyskinesis has to be on the dominant side. Scapular dyskinesis was first observed arm at rest and when performing elevations in sagittal and frontal planes with and without holding a weight (McClure et al.,

2009) (method “yes”/no”) (Uhl et al., 2009), Lateral Scapular Slide Test (LSST) (Curtis & Roush, 2006) was then used to confirm scapular asymmetry. These criteria were absent in the non-dyskinetic group.

The study was approved by the local ethics committee. Each participant was informed of the details of the study and gave their explicit consent.

Isokinetic evaluation of the protractor and retractor muscles of the shoulder

The isokinetic protocol was based on the protocol proposed and validated by Cools et al. (Cools et al., 2005; Cools, Geerooms, et al., 2007) to evaluate the concentric strength of the protractor and retractor muscles of the shoulder. The volunteers were seated, and their thorax maintained using belt to limit compensation. The shoulder was flexed at 90° and oriented to perform protraction and retraction movement in the scapular plane. The total range of motion was equal to 8 cm. Evaluations were performed on a Biodex dynamometer (Biodex Medical Systems, USA).

The resistance to fatigue was assessed at 24.4 cm/s (40 repetitions in each direction). We included more repetitions than in Cools et al. (Cools, Geerooms, et al., 2007) to be sure to elicit sufficient fatigue of the scapular muscles. The peak torque and total work were collected and normalized relatively to the body mass. Protractors:retractors ratios are also reported.

Functional evaluation of the protractor and retractor muscles of the shoulder

The volunteers were asked to perform a Knee Plus Fatigue Protocol (KPFP), which consist in repetitive active protractions and retractions of the scapula. Only the “plus” phase was performed and therefore, the elbows were to remain fully extended. This task was selected to challenge the stabilization capacities of the protractor and retractor muscles of the scapula. Indeed, the closed chain nature of the KPFP allows to induce more loads than most open chain tasks and KPFP can be used to induce fatigue to the scapular retractor/protractor muscles (Borstad et al., 2009). To limit the load on the wrists and the work of the triceps, the volunteers had their knees on the ground with the hips flexed at 90°. A metronome (90 beats per minute) was used to provide the volunteers with the required rhythm. Each beat corresponds to a pro- or retraction position. The volunteers were asked to perform this motion until they could no longer maintain the task (ten over ten on the CR10 Borg scale (Borg & Kaijser, 2006) or unable to follow the rhythm or unable to continue the task without compensations).

The electromyographic (EMG) activities of the upper and lower trapezius and serratus anterior muscles were collected with Trigno Standard and Trigno Mini sensors (Delsys, Boston, MA, USA) using silvercontact wireless bipolar bar electrodes with fixed 10 mm inter-electrode spacing. Prior to electrodes placement, skin was shaved and gently abrased and alcohol was applied for cleansing. Surface electrodes were positioned following Barbero et al. recommendations (Barbero et al., 2012). Data was acquired at a sample frequency of 1000 Hz.

The 3-dimensional position and orientation of the volunteers' thorax, and dominant/dyskinetic scapula were tracked using four Codamotion CX1 units (Charnwood Dynamics, Rothley, UK) at a sampling rate of 100 Hz. The accuracy of the system was previously evaluated (Schwartz et al., 2015). Fourteen active markers were used to follow the bony segment motion. Four markers on the thorax were placed with respect to the International Society of Biomechanics (ISB) recommendations (Wu et al., 2005). A cluster of four additional markers was attached to the sternum due to the low visibility of some thoracic markers in the push-up position. Six markers were placed on the upper posterior face of the scapula as proposed by Bourne et al. (Bourne et al., 2011) (patch 4).

During the test, hands were placed on two separate force plates (Kistler™ type 9281 EA, Kistler AG, Switzerland) to evaluate a potential transfer of the load (from one arm to another or from the upper limbs to the lower limbs). Force plates were zeroed at the beginning of each acquisition. The sampling rate of the force plates was equal to 1000 Hz.

Muscle activity, scapular kinematics and ground reaction forces were acquired twice during approximately 30 seconds: first at the beginning of the push-up plus exercise and then just before the end of the test. To anticipate the end of the test, the volunteers were asked every 20 seconds their perceived exertion using the Borg scale.

Data reduction and analysis

The thorax vertical position was used to determine the protaction (from local minima to local maxima) and retractration (from local maxima to local minima) phases of the KPFP fatigue task (Figure 1 (d)). One full cycle was define as the succession of one protraction and one retraction.

The raw EMG signals were first band pass filtered (20 - 500 Hz, zero-phase 4th order Butterworth) (Figure 1 (c)) and then filtered using a root-mean-square algorithm (100 ms moving window) (Castelein et al., 2015) to obtain the envelop. The EMG signals were normalized (Figure 1 (f)) based on maximal activation measured during Most Voluntary Isometric Contractions (MVIC) performed before the KPFP task. The procedure to obtain the Most Voluntary Activation (MVA) from the MVICs followed the procedure described in Schwartz et al. (Schwartz et al., 2017). The main steps are described thereafter. Several positions were used to obtain the Most Voluntary Activation for the volunteers (Upper trapezius: Empty can, Seated U 90°, Prone V-thumbs up, Seated U 125°, Lower trapezius: Prone V-thumbs up, Rotation 90°, Serratus Anterior: Seated U 90°, Seated T, Seated U 125°) to ensure the obtention of a reproducible MVA. Three maximal repetitions were performed for each position. The envelops (Figure 1 (b)) from the EMG signals (Figure 1 (a)) of the MVICs acquisitions were obtained following the same procedure as for the KPFP fatigue task. The maximal value (MVA) used for the normalization of each muscle was obtained using a moving filter (window size of 1s) (Figure 1 (b)). The EMG signals from the KPFP tasks were then segmented relatively to a protraction-retraction cycle (Figure 1 (h)). All cycles were average for each volunteers. Ratios of muscles active during the same phases are also computed.

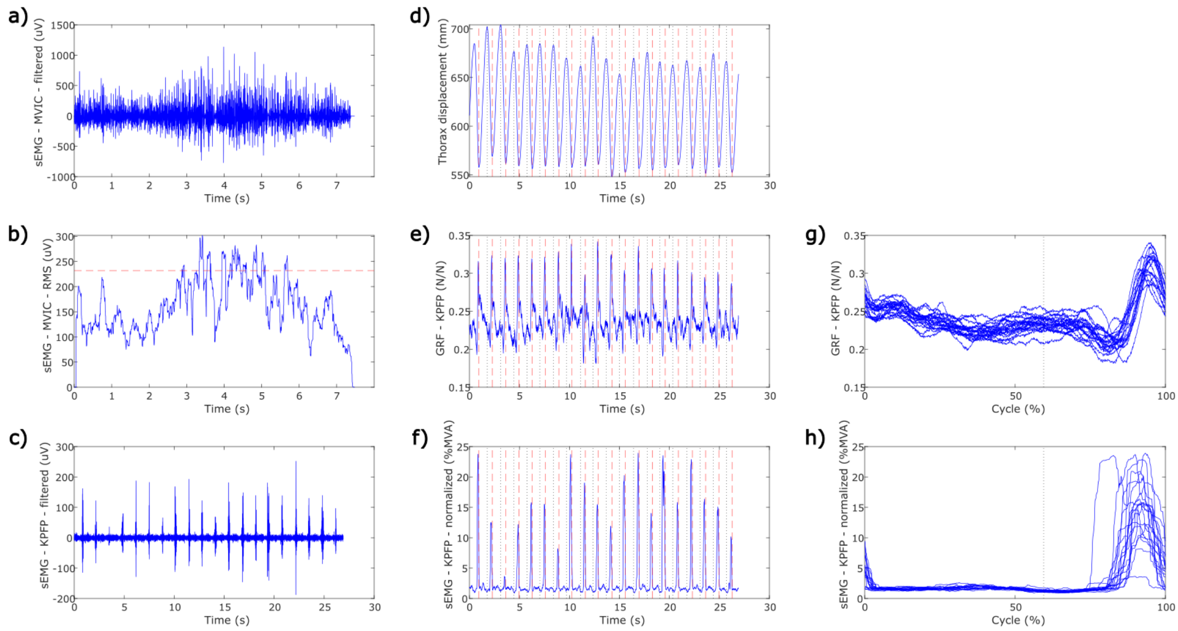


Figure 1: Illustration of the processing workflow. sEMG: the electromyographic (EMG) signal from the Most Voluntary Isometric Contraction (MVIC) task is first filtered using a band pass Butterworth filter (20-500 Hz) (a) and then filtered using a 100 ms moving RMS filter (b). The EMG Maximal Voluntary Activation (MVA) (based on a 1s moving average filter) from the MVIC tasks (red dash line in (b)) is used for normalization of the EMG signal of the KPFP (Knee Plus Fatigue Protocol) (c). Note that only one task and one repetition is shown in this figure. The normalized signal is shown in (f). Using the motion of the thorax (d), the signal is segmented in phases (lower position: vertical dash red line, upper position: vertical dot black line) (h). Ground reaction forces (GRF): the signal from the ground reaction forces (e) (only dominant side is shown on the figure) is segmented in phases (g). Scapular kinematics (not shown on the figure): the same phase segmentation is applied. The mean of all phases was kept for further (statistical) analyses.

The muscle fatigue was analysed using the methodology a Joint Analysis of EMG Spectrum and Amplitude (JASA) as described in (Luttmann et al., 2000). This method relies on the study of the evolution (before vs. after fatigue) of the signal characteristics both in the temporal (amplitude of the signal) and in the frequency (median frequency) domains. Muscle fatigue is characterized by a decrease in both the temporal and frequency domains (lower right quadrant of Figure 3).

The median frequency of the signal was also computed in order to realize

Visual3D Professional software (C-Motion, Maryland, USA) was used to evaluate the scapular kinematics. Scapular orientation was expressed relatively to the thorax using a YXZ Cardan decomposition (Wu et al., 2005). The kinematics was low pass filtered (6 Hz, zero-phase 4th order Butterworth). The scapular orientation was then expressed relatively to a protraction-retraction cycle. The kinematic data were averaged over all the protraction-retraction cycles of each acquisition.

The ground reaction forces were normalized with respected to the body mass.

Statistical analysis

Descriptive statistics of the volunteers characteristics and of the isokinetic measures are presented. If the samples were found to follow a Gaussian distribution (Shapiro-Wilk test) a parametric test (Student t- test) was used to compare both groups (i.e., non-symptomatic dyskinetic and control) (JASP, version 0.16) (JASP Team, 2021). Otherwise, a Mann-Whitney test was applied. A Welch test was used when the equality of variance assumption was violated (Levene's test). The level of significance was set at $p < 0.05$. For the Student t-test and Welch, effect size was given by Cohen's d and for the Mann-Whitney test, effect size was given by the rank biserial correlation. Effect sizes are provided and evaluated using the classification described by Cohen's d (Cohen, 1988).

To assess the modification of the muscle activation during the protraction-retraction task and between the two groups, one-dimensional statistical parametric mapping [19,20] was used (SnPM)). A mixed-model analysis of variance (ANOVA) approach was applied with a between (groups) and a within (time) group comparison. Statistical significance occurs when the SnPM curves cross the critical threshold. The associated p- values are calculated using Random Field Theory. Level of significance was also set to 0.05. This approach allows comparing the complete task cycle rather than a limited number of features such as the muscle activation peak.

The ground reaction forces and the scapular kinematics were analyzed using the same one-dimensional statistical parametric mapping method.

Results

Group characteristics

The characteristics of the dyskinetic asymptomatic group and of the healthy control group are respectively the followings: age (22.1 ± 2.4; 23.3 ± 2.2 years), height (1.8 ± 0.1; 1.8 ± 0.1 m), mass (73.2 ± 8.1; 76.4 ± 9.0 kg). The comparison of the group characteristics does not show any difference in terms of demographics (mass, height, age, t-test: $p > 0.239$).

Isokinetic evaluation

The isokinetic evaluation (Table 1) shows imbalances in the dyskinetic groups with protractor retractor ratios inferior to 0.79. Only the total work ratio is significantly smaller in the dyskinetic group even though both ratios present large effect sizes (Welch test: $p = 0.061$, effect size = 0.83 for the peak torque and Welch test: $p = 0.018$, effect size = 1.11 for the total work).

Table 1: maximal strength and fatigue resistance evaluation of the protractor and retractor muscles of the shoulder (n = 14 in the dyskinetic group and n = 11 in the healthy group). PRO: protraction; RET: retraction.

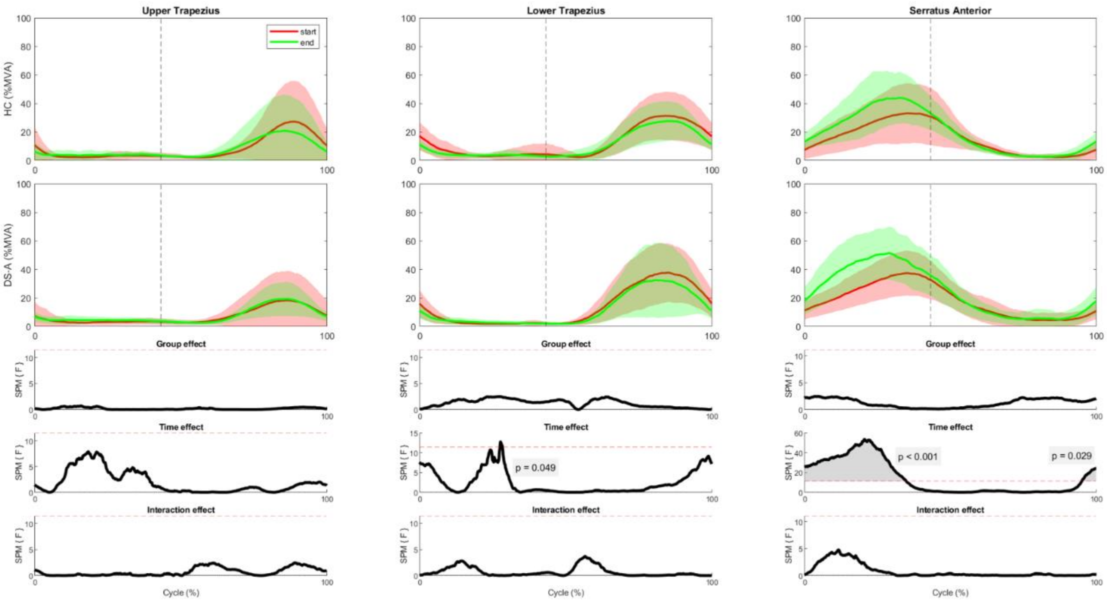
	Dyskinetic - asymptomatic		Healthy control			
	Mean **Median**	**SD** **[Q1 – Q3]**	**Mean** **Median**	**SD** **[Q1 – Q3]**	**p**	**Effect size**
Peak torque PRO (N.m/kg)[a]	4.01	0.78	3.68	0.75	0.299	0.43
Peak torque RET (N.m/kg)[a]	5.13	0.81	4.24	1.23	**0.040**	0.88
Peak torque PRO:RET[b]	0.77	[0.72 – 0.79]	0.86	[0.75 – 1.01]	0.061	0.83
Total work PRO (J/kg)[a]	44.03	9.98	42.35	12.16	0.708	0.15
Total work RET (J/kg)[a]	59.26	13.95	47.92	17.16	0.081	0.74
Total work PRO:RET[b]	[0.72 – 0.81]	0.11	0.91	[0.76 – 1.07]	**0.018**	1.11

Note. [a] Mean and SD, Student t-test applied [b] Median and [1st quartile, 3rd quartile], Welch test applied

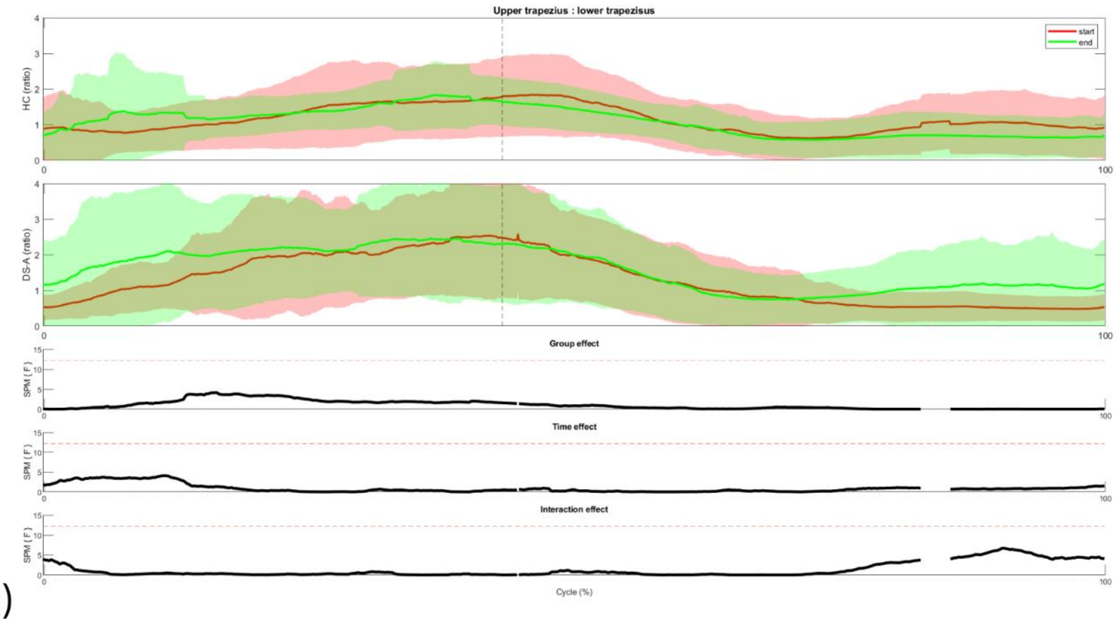
Functional evaluation (Knee Plus Fatigue Protocol)

There is no significant difference (Welch test: $p = 0.09$) concerning the duration before exhaustion between the two groups for the push-up plus task (KPFP). However, there is a tendency towards a better fatigue resistance in the dyskinetic group (effect size = 0.71) with a mean test time of 488.4 ± 237.5s against 359.7 ± 98.9s in the control group.

The EMG results (Figure 2a) shows that the upper and lower trapezius are active during the retraction phase of the exercise whereas the serratus anterior is active during the protraction phase of the exercise. The SPM statistical analysis does not identify differences of muscle activities between the two groups neither at the beginning nor at the end of the task. The results, however, show an increase of the anterior serratus muscle activity at the end of the task independently of the groups. This increase is associated with a decrease of the median frequency of the EMG signal as shown in Figure 3. This decrease is equal to 7.8% and 5.5% in the dyskinetic and healthy control groups respectively. The balance of the muscle activities shows an upper:lower trapezius ratio close to one (Figure 2b) during the active (retraction) phase of these muscles.



a)



b)

Figure 2: muscle a) activity and, b) ratios of the two groups (HC = healthy control, DS-A = dyskinetic asymptomatic) at the start of the task and at the end of the task. The vertical dotted line distinguishes the protraction and retraction phases of the task. N=10 in the Healthy group and N=13 in the Dyskinetic asymptomatic group – because of the perspiration during the fatigue task, some EMG electrodes detached for two volunteers.

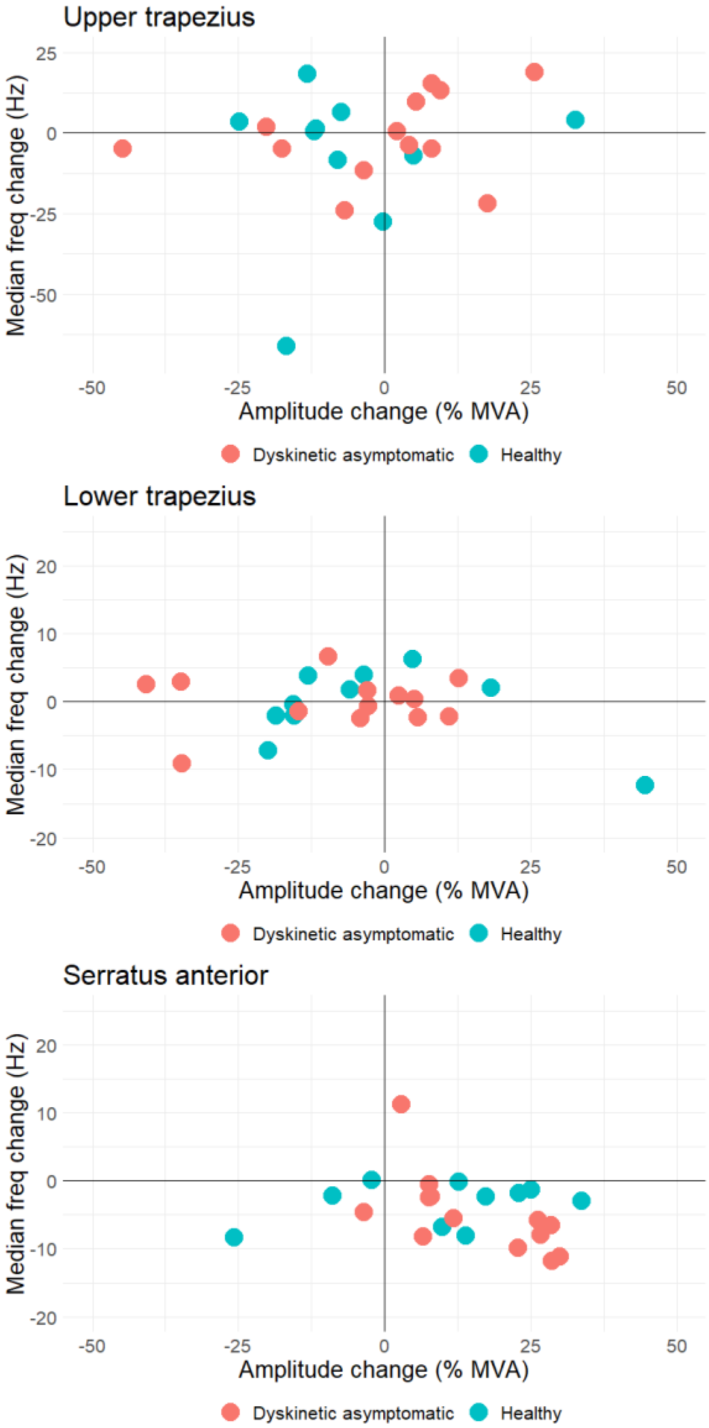


Figure 3: Joint Analysis of EMG Spectrum and Amplitude (JASA) of the evolution of the muscle activities between the start and the end of the task. N=10 in the Healthy group and N=13 in the Dyskinetic asymptomatic group – because of the perspiration during the fatigue task, some EMG electrodes detached for two volunteers.

Concerning the scapular kinematics, no statistical difference between the two groups is identified (Figure 4). However, there is a tendency towards a more anterior tilted scapula in the healthy group. In both groups, the time (fatigue) has, however, an effect on the scapular kinematics as well as on the thorax vertical displacement. The SPM analysis identifies less amplitude of motion in terms of upward rotation and anterior tilt of the scapula in particular when the shoulder is fully protracted and during the retraction phase. These modifications of the scapular kinematics are associated with a reduced vertical displacement of the thorax (the push-up plus amplitude).

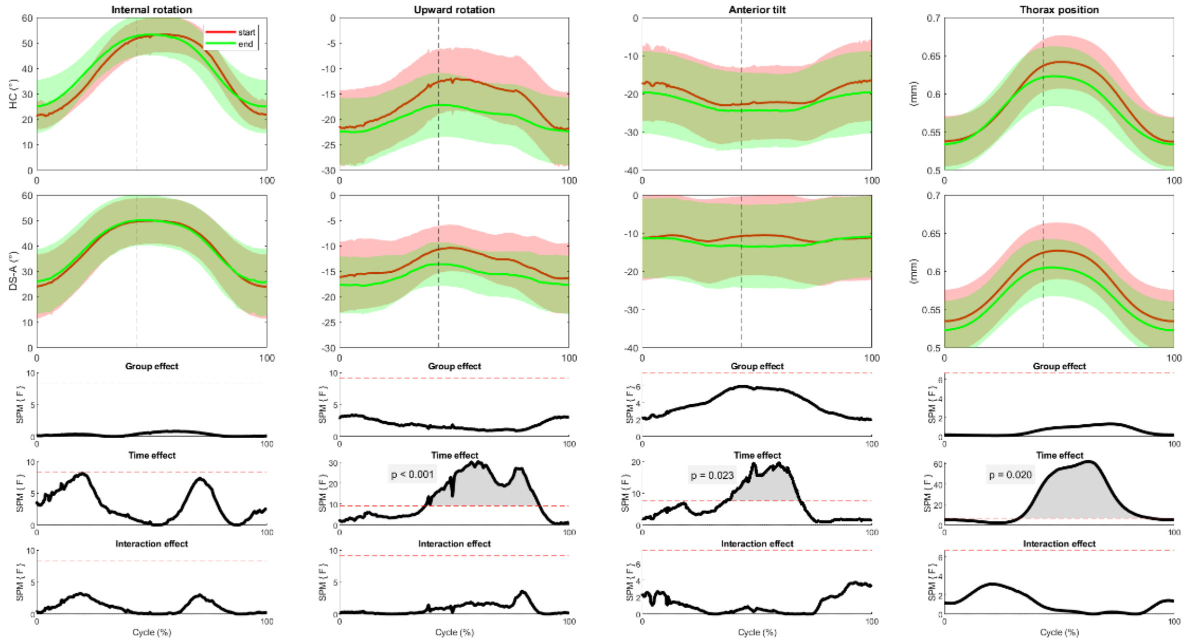


Figure 4: scapula-thoracic kinematics, thorax vertical displacement and SPM statistics of the two groups (HC = healthy control, DS-A = dyskinetic asymptomatic) at the start of the task and at the end of the task. N=11 in each group – because of the perspiration during the fatigue task, some markers detached for four volunteers. Note that upward rotation and anterior tilt are described by negative values.

The ground reaction force ratio between the arm of interest and the contralateral side is close to 1 in all conditions and groups (between 1.03 ± 0.01 and 1.07 ± 0.02) demonstrating a good balance between both sides. The SPM analysis does not reveal any significant differences between times/groups.

Discussion and implication

There is a debate in the literature whether dyskinesis should be considered as a risk factor of shoulder injury (Clarsen et al., 2014; Hickey et al., 2018) even if a more recent meta-analysis (Hogan et al., 2021) tends to demonstrate that scapular dyskinesis alone is not a risk factor of shoulder injuries. Some authors (Møller et al., 2017) also suggested that dyskinesis may however exacerbate other risk factors. To better understand scapular dyskinesis there is an interest to study dyskinetic individuals who do not suffer from any pathology, injury or pain which may introduce confounding factors (i.e., asymptomatic). These confounding factors may mask the specific effects of dyskinesis. Because of the importance of the stabilizing muscles of the scapula (i.e., protractors and retractors) in dyskinesis (Kibler et al., 2013), the present study investigated the strength and fatigue characteristics as well as the activation patterns of the protractor and retractor muscles of the scapula during a closed-chain exercise. The functional test aimed to evaluate the stabilizers of the scapula in more challenging conditions that is increased loads and fatigue in comparison to open-chained exercises.

A balance of the agonist and antagonist muscles, in terms of strength and activation patterns, is usually expected to control the position and movement of the scapula. Our results demonstrates muscle force (and fatigue resistance) imbalances in both our groups with protractor/retractor ratio inferior to one. The imbalances were however majored in the dyskinetic group. Previous studies have also found lower ratios in symptomatic and dyskinetic groups in comparison to control groups. For instance, Cools et al. (Cools et al., 2005) have reported strength ratios inferior to one for athletes with impingement symptoms but not for healthy controls. In a recent publication using a similar protocol than the present study, symptomatic (at least three of the five tendinous tests were positive) dyskinetic sportsmen present strength and fatigue resistance ratio equal to 0.7 (Martens et al., 2023). Our observations tend to indicate that strength imbalances in dyskinetic athletes appear before pain/injury. Clinical evaluation of the scapular dyskinesis, as performed in this study, could therefore be complemented by a strength and/or fatigue resistance evaluation.

Analytical evaluations such as isokinetic evaluations only provide information concerning the maximal strength and fatigue resistance capacities of the muscle groups. Muscle activities during functional tasks provide important complementary information as they reveal the muscles coordination patterns that will contribute to the scapula positioning (McQuade et al., 2016). Concerning the protraction and retraction of the scapula, several ratios of muscle activity have been evaluated in the literature (Cools, Dewitte, et al., 2007) to reflect the control of the scapula including upper trapezius:serratus anterior, upper trapezius:middle trapezius and upper trapezius:lower trapezius. A previous study (Tooth, Schwartz, et al., 2020) has shown that dyskinetic overhead players present increased ratios (23-70%)

in comparison to non-dyskinetic ones during an open-chain exercise. We did not find similar differences in our closed-chain exercise demonstrating the different stabilization strategies and the complementarity of the open and closed-chain exercises. Our results also exhibit that the upper and lower trapezius muscles on one hand, and the serratus anterior muscle, on the other hand, are not active during the same phases of the KPFP. Indeed, the serratus anterior muscle was active during the protraction phase (concentric phase) whereas the trapezius muscles were active during the retraction phase (eccentric phase) for most volunteers. Several authors found low upper trapezius: serratus anterior ratios (<0.2 for most exercises) both during the concentric and eccentric phases (Ludewig et al., 2004; Patselas et al., 2021) demonstrating a more continuous activity of the serratus anterior. The limited activity of the serratus anterior in our study cannot be explained by a report of the load on the contralateral arm and/or the lower limbs as demonstrated by the ground reaction forces measurements. Several (non-exclusive) hypotheses may explain the absence of synchronous muscular activity during the same phases including a reduced load applied to the shoulder (in comparison to other push-up task modalities), the cadence of the exercise and/or a lack of neuromuscular control of the scapula. These patterns were present in both groups as no differences of muscle activities were found. These results would tend to demonstrate that asymptomatic dyskinesis may not always directly relate to muscle activation alterations. In addition to strength imbalances, soft tissues alterations such as muscle stiffness, tendon properties (Reuther et al., 2015), posterior shoulder tightness and pectoralis minor length (related with scapular forward posture (Laudner et al., 2010; Lee et al., 2015)) may be of interest but have not been investigated in the present study. From a methodological point of view, our EMG results also illustrate the interest to report full EMG signals rather than mean activation (Horsak et al., 2017) or activation at specific events (Seo et al., 2013). EMG ratios, based on mean values, do not correctly convey the timing of the activities of the muscles.

In addition to muscle balance, fatigue of the scapular muscles have been previously associated with alterations of the scapula-thoracic and scapulo-humeral rhythm (McQuade et al., 1998) which justify the implementation of our fatigue protocol performed until exhaustion. The induction of fatigue during the functional task induced modifications of the scapular kinematics in both groups. With fatigue, less amplitude of scapular motion is observed, which leads to a more upwardly rotated and anteriorly tilted scapula at full protraction (push up plus position). The observed modifications are probably partially related to the inability of the volunteers to maintain the same amplitude of thorax motion with the increase of fatigue. The modifications may also be related to some difficulty to maintain a correct positioning of the scapula with respect with the thorax. Indeed, Borstad et al. (Borstad et al., 2009) also observed an increase of the anterior tilt with fatigue during an isometric push-up plus task. We, however, did not observe an increase of the internal rotation of the scapula as they did. Compared to push up plus exercises previously described in the literature, our exercise may not have induced as much fatigue to the scapular muscles. Indeed, in a previous study (Borstad et al., 2009), the median frequency decrease in the serratus anterior EMG signal during the push-up plus task was equal to 27.2% against 5.5 to 7.8% in our study. A significant increase of the amplitude of the serratus anterior activity at the end of the push-up plus task is coherent with the development of muscular fatigue (Luttmann et al., 2000). We did not identify muscular fatigue of the lower and upper trapezius. In Borstad et al. study, the volunteers were in a push-up plus position with their feet and hands in contact with the ground, while, in our study, the knees and hands were in contact with the ground. This position probably increases the load applied to the upper limbs and the scapula and could explain the increased fatigue. Likewise, in Ludewig et al. study (Ludewig et al., 2004), hips were not flexed at 90° like in our study, contributing to increased loads. Ludewig et al. reported maximal serratus anterior activity (between 60 and 120% depending on the exercises) which is superior to the activities observed in the present study. One should, however, remain careful as the EMG signal normalization process was not similar and could have influenced the reported normalized activation as demonstrated in Schwartz et al. (Schwartz et al., 2017).

Some limitations of the present study could provide guidance to future studies. The size of the groups could be further extended and include female volunteers to confirm the results obtained in this study. Female volunteers were not included because both gender may not have the same scapular kinematics (Schwartz et al., 2016) and could have represented a confounding factor. This study, however, offers a large biomechanical investigation of the protractor and retractor muscles of the scapula. It includes analytical evaluation of strength and fatigue, as well as a kinematic and neuromuscular evaluation during a functional task inducing fatigue. The induced fatigue of serratus anterior muscle was lower than expected and reported in other studies. This result may be due to our choice to limit the load applied to the upper limb (knees on the floor and hips flexed at 90°). If this position may not induce as much fatigue to the protractor and retractor muscles, it has the advantage to be easier to perform by patients in a clinical context. Despite the limited fatigue, significant modifications of the scapulo-thoracic kinematics were observed as well as a reduced amplitude of motion of the thorax.

Conclusions

This study was able to identify limited differences in the profiles of an asymptomatic dyskinetic group and a non dyskinetic group. These differences were mainly related to strength characteristics (and in particular of fatigue resistance) but not to kinematics or muscle activation patterns. From the results of the study, the implication of the modified force profiles on the functional gesture and therefore on injury risk and performance is still conjectural. The asymptomatic dyskinetic sportsmen already presented protractors vs. retractors imbalances, which demonstrate that strength imbalances are not necessarily related to the presence of pain or injury for dyskinetic subjects. Furthermore, our results illustrate that clinical evaluation of the dyskinesia is not sufficient to characterize the biomechanics of the shoulder and should be completed by strength evaluations. Finally, we have observed that a push-up plus exercise performed with the hip at 90° does not favour a synchronized activity of the trapezius and serratus anterior muscles and may therefore present a lesser interest for a scapular motor rehabilitation. Concerning other stabilization exercise programs the reader can refer to recent systematic reviews (Ravichandran et al., 2020; Zhong et al., 2024). More functional approaches including various conditions (in terms of velocity, stretching, perturbation) may also be of interest and should be further investigated as suggested by (McQuade et al., 2016).

References

Barbero, M., Merletti, R., & Rainoldi, A. (2012). *Atlas of Muscle Innervation Zones*. Springer Milan. https://doi.org/10.1007/978-88-470-2463-2

Ben Kibler, W. (1998). The Role of the Scapula in Athletic Shoulder Function. *The American Journal of Sports Medicine*, *26*(2), 325–337. https://doi.org/10.1177/03635465980260022801

Borg, E., & Kaijser, L. (2006). A comparison between three rating scales for perceived exertion and two different work tests. *Scandinavian Journal of Medicine and Science in Sports*, *16*(1), 57–69. https://doi.org/10.1111/j.1600-0838.2005.00448.x

Borstad, J. D., Szucs, K., & Navalgund, A. (2009). Scapula kinematic alterations following a modified push-up plus task. *Human Movement Science*, *28*(6), 738–751. https://doi.org/10.1016/j.humov.2009.05.002

Bourne, D. a., Choo, A. M., Regan, W. D., MacIntyre, D. L., & Oxland, T. R. (2011). The Placement of Skin Surface Markers for Non-Invasive Measurement of Scapular Kinematics Affects Accuracy and Reliability. *Annals of Biomedical Engineering*, *39*(2), 777–785. https://doi.org/10.1007/s10439-010-0185-1

Castelein, B., Cagnie, B., Parlevliet, T., Danneels, L., & Cools, A. (2015). Optimal Normalization Tests for Muscle Activation of the Levator Scapulae, Pectoralis Minor, and Rhomboid Major: An Electromyography Study Using Maximum Voluntary Isometric Contractions. *Archives of Physical Medicine and Rehabilitation*, *96*(10), 1820–1827. https://doi.org/10.1016/j.apmr.2015.06.004

Clarsen, B., Bahr, R., Andersson, S. H., & Munk, R. (2014). Reduced glenohumeral rotation, external rotation weakness and scapular dyskinesis are risk factors for shoulder injuries among elite male handball players: a prospective cohort study. *Br J Sports Med*, *48*, 1327–1333. https://doi.org/10.1136/bjsports-2014-093702

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences* (2nd ed.). Lawrence Erlbaum Associates.

Cools, A. M., Dewitte, V., Lanszweert, F., Notebaert, D., Roets, A., Soetens, B., Cagnie, B., & Witvrouw, E. E. (2007). Rehabilitation of scapular muscle balance: which exercises to prescribe? *The American Journal of Sports Medicine*, *35*(10), 1744–1751. https://doi.org/10.1177/0363546507303560

Cools, A. M., Geerooms, E., Van Den Berghe, D. F. M., Cambier, D. C., & Witvrouw, E. E. (2007). Isokinetic scapular muscle performance in young elite gymnasts. *Journal of Athletic Training*, *42*(4), 458–463.

Cools, A. M., Witvrouw, E. E., Mahieu, N. N., & Danneels, L. a. (2005). Isokinetic scapular muscle performance in overhead athletes with and without impingement symptoms. *Journal of Athletic Training*, *40*(2), 104–110.

Curtis, T., & Roush, J. R. (2006). The lateral scapular slide test: a reliability study of males with and without shoulder pathology. *North American Journal of Sports Physical Therapy*, *1*(3), 140–146.

Forthomme, B., Dvir, Z., Crielaard, J. M., & Croisier, J.-L. (2011). Isokinetic assessment of the shoulder rotators: a study of optimal test position. *Clinical Physiology and Functional Imaging*, *31*(3), 227–232. https://doi.org/10.1111/j.1475-097X.2010.01005.x

Hickey, D., Solvig, V., Cavalheri, V., Harrold, M., & Mckenna, L. (2018). Scapular dyskinesis increases the risk of future shoulder pain by 43% in asymptomatic athletes: a systematic review and meta-analysis. *British Journal of Sports Medicine*, *52*(2), 102–110. https://doi.org/10.1136/bjsports-2017-097559

Hogan, C., Corbett, J. A., Ashton, S., Perraton, L., Frame, R., & Dakic, J. (2021). Scapular Dyskinesis Is Not an Isolated Risk Factor for Shoulder Injury in Athletes: A Systematic Review and Meta-analysis. *American Journal of Sports Medicine*, *49*(10), 2843–2853. https://doi.org/10.1177/0363546520968508

Horsak, B., Kiener, M., Pötzelsberger, A., & Siragy, T. (2017). Serratus anterior and trapezius muscle activity during knee push-up plus and knee-plus exercises performed on a stable, an unstable surface and during sling-suspension. *Physical Therapy in Sport*, *23*, 86–92. https://doi.org/10.1016/j.ptsp.2016.08.003

Inman, V. T., Saunders, J. B. D., & Abbott, L. C. (1944). Observations on the function of the shoulder joint. *The Journal of Bone & Joint Surgery*, *26*(1), 1–30.

JASP Team. (2021). *JASP (Version 0.16)[Computer software]*. https://jasp-stats.org/

Kibler, W. Ben, Ludewig, P. M., McClure, P. W., Michener, L. A., Bak, K., & Sciascia, A. D. (2013). Clinical implications of scapular dyskinesis in shoulder injury: The 2013 consensus statement from the "scapular summit." *British Journal of Sports Medicine*, *47*(14), 877–885. https://doi.org/10.1136/bjsports-2013-09242

Kibler, W. (2006). Classification and treatment of scapular pathology. In T. Ellenbecker (Ed.), *Shoulder Rehabilitation. Non-Operative Treatment*. Thieme. https://doi.org/10.5005/jp/books/12869_245

Kibler, W., Sciascia, A., & Wilkes, T. (2012). Scapular dyskinesis and its relation to shoulder injury. *Journal of the American Academy of Orthopaedic Surgeons*, *20*(6), 364–372. https://doi.org/10.5435/JAAOS-20-06-364

Laudner, K. G., Moline, M. T., & Meister, K. (2010). The relationship between forward scapular posture and posterior shoulder tightness among baseball players. *American Journal of Sports Medicine*, *38*(10), 2106–2112. https://doi.org/10.1177/0363546510370291

Lee, J. H., Cynn, H. seock, Yi, C. H., Kwon, O. yun, & Yoon, T. L. (2015). Predictor variables for forward scapular posture including posterior shoulder tightness. *Journal of Bodywork and Movement Therapies*, *19*(2), 253–260. https://doi.org/10.1016/j.jbmt.2014.04.010

Lin, D. J., Wong, T. T., & Kazam, J. K. (2018). Shoulder injuries in the overhead-throwing athlete: Epidemiology, mechanisms of injury, and imaging findings. *Radiology*, *286*(2), 370–387. https://doi.org/10.1148/radiol.2017170481

Ludewig, P. M., Hoff, M. S., Osowski, E. E., Meschke, S. A., & Rundquist, P. J. (2004). Relative Balance of Serratus Anterior and Upper Trapezius Muscle Activity during Push-Up Exercises. *American Journal of Sports Medicine*, *32*(2), 484–493. https://doi.org/10.1177/0363546503258911

Luttmann, A., Jäger, M., & Laurig, W. (2000). Electromyographical indication of muscular fatigue in occupational field studies. *International Journal of Industrial Ergonomics*, *25*(6), 645–660. https://doi.org/10.1016/S0169-8141(99)00053-0

Martens, G., Gofflot, A., Tooth, C., Schwartz, C., Bornheim, S., Croisier, J.-L., Kaux, J.-F., & Forthomme, B. (2023). Differences in strength and fatigue resistance of scapular protractors and retractors between symptomatic and asymptomatic dyskinesis. *Journal of Athletic Training*. https://doi.org/10.4085/1062-6050-0092.23

McClure, P., Tate, A. R., Kareha, S., Irwin, D., & Zlupko, E. (2009). A Clinical Method for Identifying Scapular Dyskinesis, Part 1: Reliability. *Journal of Athletic Training*, *44*(2), 160–164. https://doi.org/10.4085/1062-6050-44.2.160

McQuade, K. J., Borstad, J., & de Oliveira, A. S. (2016). Critical and Theoretical Perspective on Scapular Stabilization: What Does It Really Mean, and Are We on the Right Track? *Physical Therapy*, *96*(8), 1162–1169. https://doi.org/10.2522/ptj.20140230

McQuade, K. J., Dawson, J., & Smidt, G. L. (1998). Scapulothoracic Muscle Fatigue Associated With Alterations in Scapulohumeral Rhythm Kinematics During Maximum Resistive Shoulder Elevation. *Journal of Orthopaedic & Sports Physical Therapy*, *28*(2).

Møller, M., Nielsen, R. O., Attermann, J., Wedderkopp, N., Lind, M., Sørensen, H., & Myklebust, G. (2017). Handball load and shoulder injury rate: A 31-week cohort study of 679 elite youth handball players. *British Journal of Sports Medicine*, *51*(4), 231–237. https://doi.org/10.1136/bjsports-2016-096927

Moraes, G. F. S., Faria, C. D. C. M., & Teixeira-Salmela, L. F. (2008). Scapular muscle recruitment patterns and isokinetic strength ratios of the shoulder rotator muscles in individuals with and without impingement syndrome. *Journal of Shoulder and Elbow Surgery*, *17*(1 SUPPL.), 48–53. https://doi.org/10.1016/j.jse.2007.08.007

Noreski, M. A., & Cohen, S. B. (2015). Epidemiology of Shoulder Injuries in Overhead Athletes. In *Sports Injuries to the Shoulder and Elbow* (pp. 23–34). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-41795-5_2

Patselas, T., Karanasios, S., Sakellari, V., Fysekis, I., Patselas, M. I., & Gioftsos, G. (2021). EMG activity of the serratus anterior and trapezius muscles during elevation and PUSH UP exercises. *Journal of Bodywork and Movement Therapies*, *27*, 247–255. https://doi.org/10.1016/j.jbmt.2021.02.002

Ravichandran, H., Janakiraman, B., Gelaw, A. Y., Fisseha, B., Sundaram, S., & Sharma, H. R. (2020). Effect of scapular stabilization exercise program in patients with subacromial impingement syndrome: a systematic review. *Journal of Exercise Rehabilitation*, *16*(3), 216–226. https://doi.org/10.12965/jer.2040256.128

Reuther, K. E., Thomas, S. J., Tucker, J. J., Vafa, R. P., Gordon, J. A., Liu, S. S., Caro, A. C., Yannascoli, S. M., Kuntz, A. F., & Soslowsky, L. J. (2015). Overuse Activity in the Presence of Scapular Dyskinesis Leads to Shoulder Tendon Damage in a Rat Model. *Annals of Biomedical Engineering*, *43*(4), 917–928. https://doi.org/10.1007/s10439-014-1137-y

Rockwood, C. A., Matsen, F. A., Wirth, M. A., & Lippitt, S. B. (2004). *The Shoulder* (3rd ed.). Saunders.

Schwartz, C., Croisier, J. L., Rigaux, E., Brüls, O., Denoël, V., & Forthomme, B. (2016). Gender effect on the scapular 3D posture and kinematic in healthy subjects. *Clinical Physiology and Functional Imaging*, *36*(3), 188–196. https://doi.org/10.1111/cpf.12212

Schwartz, C., Denoël, V., Forthomme, B., Croisier, J.-L., & Brüls, O. (2015). Merging multi-camera data to reduce motion analysis instrumental errors using Kalman filters. *Computer Methods in Biomechanics and Biomedical Engineering*, *18*(9), 952–960. https://doi.org/10.1080/10255842.2013.864640

Schwartz, C., Tubez, F., Wang, F.-C., Croisier, J.-L., Brüls, O., Denoël, V., & Forthomme, B. (2017). Normalizing shoulder EMG: An optimal set of maximum isometric voluntary contraction tests considering reproducibility. *Journal of Electromyography and Kinesiology*, *37*, 1–8. https://doi.org/10.1016/j.jelekin.2017.08.005

Seo, S. H., Jeon, I. H., Cho, Y. H., Lee, H. G., Hwang, Y. T., & Jang, J. H. (2013). Surface EMG during the push-up plus exercise on a stable support or Swiss ball: Scapular stabilizer muscle exercise. *Journal of Physical Therapy Science*, *25*(7), 833–837. https://doi.org/10.1589/jpts.25.833

Tooth, C., Croisier, J.-L., Schwartz, C., TUBEZ, F., Gofflot, A., Bornheim, S., & Forthomme, B. (2022). The influence of growth and development on shoulder rotators strength in young male and female elite tennis players. *The Journal of Sports Medicine and Physical Fitness*, *62*(12), 1638–1645. https://doi.org/10.23736/S0022-4707.22.13422-5

Tooth, C., Gofflot, A., Schwartz, C., Croisier, J. L., Beaudart, C., Bruyère, O., & Forthomme, B. (2020). Risk Factors of Overuse Shoulder Injuries in Overhead Athletes: A Systematic Review. *Sports Health*, *12*(5), 478–487. https://doi.org/10.1177/1941738120931764

Tooth, C., Schwartz, C., Croisier, J.-L., Bornheim, S., Brüls, O., Denoël, V., & Forthomme, B. (2020). Activation Profile of Scapular Stabilizing Muscles in Asymptomatic People. *American Journal of Physical Medicine & Rehabilitation*, *99*(10), 925–931. https://doi.org/10.1097/PHM.0000000000001446

Uhl, T. L., Kibler, W. Ben, Gecewich, B., & Tripp, B. L. (2009). Evaluation of Clinical Assessment Methods for Scapular Dyskinesis. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, *25*(11), 1240–1248. https://doi.org/https://doi.org/10.1016/j.arthro.2009.06.007

Wu, G., Vanderhelm, F., Dirkjanveeger, H., Makhsous, M., Vanroy, P., Anglin, C., Nagels, J., Karduna, A., Mcquade, K., & Wang, X. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - Part II: shoulder, elbow, wrist and hand. *Journal of Biomechanics*, *38*(5), 981–992. https://doi.org/10.1016/j.jbiomech.2004.05.042

Zago, M., Kawczyński, A., Klich, S., Pietraszewski, B., Galli, M., & Lovecchio, N. (2020). Fatigue-Induced Scapular Dyskinesis in Healthy Overhead Athletes. *Frontiers in Bioengineering and Biotechnology*, *8*. https://doi.org/10.3389/fbioe.2020.00302

Zhong, Z., Zang, W., Tang, Z., Pan, Q., Yang, Z., & Chen, B. (2024). Effect of scapular stabilization exercises on subacromial pain (impingement) syndrome: a systematic review and meta-analysis of randomized controlled trials. *Frontiers in Neurology*, *15*. https://doi.org/10.3389/fneur.2024.1357763