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Children and adolescents with all forms of shoulder instability demonstrate differences in their movement and muscle activity patterns when compared to age- and sex-matched controls

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Hypothesis and Background: Shoulder instability (SI) is a complex impairment, and identifying biomarkers that differentiate subgroups is challenging. Children and adolescents with SI (irrespective of etiology) have differences in their movement and muscle activity profiles compared to age- and sex-matched controls (2-tailed). There are limited fundamental movement and muscle activity data for identifying different mechanisms for SI in children and adolescents that can inform subgrouping and treatment allocation.
Methods: Young people between 8 and 18 years were recruited into 2 groups of SI and age- and sex-matched controls (CG). All forms of SI were included, and young people with coexisting neurologic pathologies or deficits were excluded. Participants attended a single session and carried out 4 unweighted and 3 weighted tasks in which their movements and muscle activity was measured using 3-dimensional (3D) movement analysis and surface electromyography (sEMG). Statistical parametric mapping was used to identify between-group differences.
Results: Data were collected for 30 young people (15 SI [6 male, 9 female] and 15 CG [8 male, 7 female]). The mean (standard deviation) age of the participants was 13.6 years (3.0). The SI group demonstrated consistently more protracted and elevated sternoclavicular joint positions during all movements. Normalized muscle activity in latissimus dorsi was lower in the SI group and had the most statistically significant differences across all movements. Where differences were identified, the SI group also had increased normalized activity of their middle trapezius, posterior deltoid, and biceps muscles but decreased activity of their latissimus dorsi, triceps and anterior deltoid muscles compared with the CG group. No statistically significant differences were found for the pectoralis major across any movements. Weighted tasks produced fewer differences in muscle activity patterns compared with unweighted tasks.
Discussion and Conclusion: Young people with SI may adapt their movements to minimize glenohumeral joint instability. This was demonstrated by reduced variability in acromioclavicular and sternoclavicular joint angles, adoption of different movement strategies across the same joints, and increased activity of the scapular stabilizing muscles, despite achieving similar arm positions to the CG.

Ethical approval for this study was gained from the Health Research Authority West Midlands–South Birmingham Research Ethics Committee (REF: 20/WM/0021). This trial is registered on ClinicalTrials.gov Identifier: NCT04267354 available at: https://clinicaltrials.gov/ct2/show/NCT04311216.

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Young people with SI demonstrated consistent differences in their muscle activity and movement patterns. Consistently observed differences at the shoulder girdle included increased sternoclavicular protraction and elevation accompanied by increased normalized activity of the posterior scapula–stabilizing muscles. Existing methods of measurement may be used to inform clinical decision making; however, further work is needed to evaluate the prognostic and clinical utility of derived 3D and sEMG data for informing decision making within SI.

Level of evidence: Level III; Case Control Design; Epidemiology Study

Keywords: Shoulder; instability; biomechanics; electromyography; motion analysis; dislocation

Shoulder instability is a complex impairment that manifests as excessive translation between the humerus and glenoid resulting in partial subluxation or complete dislocation of the glenohumeral joint. A plethora of classification systems exist that seek to identify pathophysiological mechanisms that are causal or contributory to the presentation of shoulder instability. Broadly, classification systems describe injury mechanisms (traumatic or atraumatic), instability direction, frequency and severity (subluxation and dislocation), and role of body structures and functions (bony morphology, supporting capsular and ligamentous structures and ‘‘muscle patterning’’).[18,24,25,30] Psychosocial factors are associated with the impairment but are not explicitly identified in existing models.[23,25,30,41,49] Identification of the most significant factors is important for improving patient outcomes through timely assessment, referral, and appropriate treatment allocation.

Previous research has shown the value of additional imaging or measurement modalities for subgrouping shoulder instability patients and highlights the errors that can occur when using frameworks dependent on patient-reported outcomes and clinical observations, particularly for atraumatic or multidirectional instability [18,19,38] Moroder et al[38] identified that in ‘‘functional instability,’’ multidirectional instability was less common than anticipated when assessed using fluoroscopy, and between 10% and 20% of patients had evidence of bony morphologic changes identified on MRI. These case findings are discussed as being unlikely to have a significant biomechanical effect on shoulder stability, and pathologic muscle patterns are considered as the most likely cause, despite no electromyography or musculoskeletal modeling analysis.[38] Jaggi et al[18] identified that 8 of 81 participants (10%) were not appropriate for the study after initial categorization of type 2 instability, because of either no capsulolabral damage or bony injury, identified only after arthroscopic investigation for eligibility.[30] Accurate subgrouping of patients in both studies was achieved using methods not readily available in clinical practice. Misclassification of patients may be underestimated and highlights the complexity of accurate mechanism identification.

Existing research has helped elucidate mechanisms regarding shoulder instability.[19,38,57] However, it is worth noting that between studies most have been unable to longitudinally measure physiological changes, have no normative data prior to the development of instability, are predicated on existing clinical classification frameworks, or measured a selective number of muscles and movements.[19,38,57] This likely reflects the challenges of conducting research in this area, where pragmatic study designs for evaluating mechanisms in a complex patient group are required. In some cases, conclusions regarding biomechanical outcomes and mechanisms not measured, for example, muscle force, are based on other measured biomechanical outcomes, for example, kinematics and surface electromyography (sEMG), which although related are not equivalent or interchangeable.[32,36,39,51] Any inferences regarding causal mechanisms should therefore be considered with this understanding.

Considerable emphasis has been placed on the role of the shoulder muscles and their activity profiles, often referred to as ‘‘muscle patterning,’’ in both the diagnosis and rehabilitation of shoulder instability.[30] Determining whether muscle activity patterns are primary causes of pathology, secondary adaptations, or variations within a spectrum of typical movements is challenging. This differentiation requires (1) robust measurement methods and (2) an understanding of normal variability and suitable reference data, for example, kinematics or muscle activity profiles. Three-dimensional movement analysis, which includes sEMG, is used routinely in clinical practice to inform decision making in complex patient groups with disordered control.[3,27,47,58] Barriers to more widespread use in clinical upper-limb services include a lack of clinical standards and limited reference protocols and tasks.[47] A lack of consensus on methods for recording and reporting, for example, normalization or reporting of EMG signals, makes synthesizing the literature challenging, which can be a further barrier for translation to clinical practice.[53] Determining thresholds for diagnosis of pathologic movement or muscle activity problems is also particularly challenging in the upper limb, owing to the degrees-of-freedom or redundancy problem.[40] With more than 70 muscles and 34 rotational degrees of freedom available in the upper limb, a single task may have potentially infinite combinations of viable force solutions across the muscles and joints that need to be solved for neuromuscular control. Comparison between different tasks further compounds this complexity. Differences between individuals and groups may therefore reflect a range of feasible solution spaces in which the neuromusculoskeletal system is adapting and optimizing for the constraint of stability in the light of underlying congenital, developmental, or acquired bony morphology and soft tissue ligamentous changes that may be static or dynamic.[40]

A recent systematic review provides moderate evidence for those with multidirectional instability as having consistent patterns of prolonged or higher rotator muscle activity during a range of shoulder movements.[57] Muscles involved in movement of the arm and shoulder girdle were found to have variable timing and levels of activity during movements. Differences in muscle activity patterns were accompanied by decreased upward rotation and increased internal rotation during elevation of the scapula. Existing research has mainly focused on instability mechanisms in adults and adolescents, with the majority of research conducted on the former. Children and adolescents who present with instability and an unclear mechanism are known to be complex and highly variable, possibly as the developing adolescent system is in an ongoing process of learning and adaptation to evolving maturation-related changes.[31,33,38] Existing practices regarding diagnosis and rehabilitation, particularly in children and adolescents, would benefit from further evidence regarding muscles activity and movement patterns, particularly in atraumatic instability as this can affect children at any age and extend into adulthood.[10,41,43] The aim of this proof-of-concept study was to identify if there are any movement and muscle activity differences between young people with shoulder instability and age- and sex-matched controls and quantify these differences where they exist. Our hypothesis was nondirectional, with the null hypothesis being that there are no differences between the movement and muscle activity of young people with shoulder instability, irrespective of etiology (SI), and age- and sex-matched controls (CG).

Materials and methods

This work was part of a prospective longitudinal case-control study of young people with and without shoulder instability. This article describes the baseline biomechanical measurements and identified movement and muscle activity differences between groups.

Study design

This study recruited participants from 2 different sampling frames. These were a group of young people with shoulder instability (SI) and an age- and sex-matched control group (CG). Participants were recruited from a single tertiary center and the study was advertised across regional clinical centers and social media. A total of 5 additional centers signposted participants to the study. Recruitment was over a 24-month period. The overall recruitment rate was 81%, with 7 of 37 participants approached declining or unable to take part in the study. As this was a proof-of-concept study, a priori sample size was informed by previous studies investigating upper-limb function using 3-dimensional (3D) motion capture.[20,21] The selected sample size was also appropriate for detecting between-group differences, using statistical parametric mapping analysis.[34]

Following informed consent to participate in the study, all participants attended a single measurement session for demographic, clinical, and 3D-movement assessment of their upper limb. Participants were provided with paper diaries to record their instability episodes and followed up on a monthly basis for 1 year using phone calls and electronic communications to record any episodes of instability.

Inclusion criteria

For both groups, young people aged between 8 and 18 years were included unless there were any coexisting neurologic pathologies or deficits. For the SI group, individuals were included if they had symptomatic instability with at least 1 sign of positive instability on clinical examination during the sulcus, apprehension, or anterior and posterior shift load tests. This included patients with all forms of instability, that is, recurrent, first-time, multidirectional, atraumatic, and traumatic instability and those who had instability following previous surgery.

Exclusion criteria

For the SI group, subjects were excluded if they were previously surgically managed and did not have any further episodes of instability following the intervention. For the CG, subjects were excluded if they had any previous presentation to a health care professional with a diagnosis of shoulder instability, a shoulder injury within the last 3 months on the arm being assessed that had not resolved, previous surgical intervention on the arm being assessed or ongoing or pending medical management, and diagnostic investigations or rehabilitation on the arm being assessed.

Demographic and clinical assessments

Clinical assessments included recording of the following instability features: type (single episode or recurrent), apprehension, guarding or laxity in the sulcus, anterior and posterior shift load, and apprehension relocation test, as well as Beighton score of hypermobility. Additional questions included relevant medical history, time since last instability episode, side(s) of instability, self-reported dislocation or subluxation, and direction and number of subluxation or dislocation episodes. Grip strength was assessed bilaterally using a Jamar hydraulic hand dynamometer. Participants performed the testing with the elbow flexed to 90° and carried out 3 measures each side with encouragement from the assessor to squeeze as hard as they could throughout. The maximum value recorded is reported.

3D movement analysis measurement protocol

An overview of the marker cluster and sEMG placement for data collection is shown in Figure 1. Retroreflective marker clusters were placed on the thorax, acromion, humerus, forearm, and hand

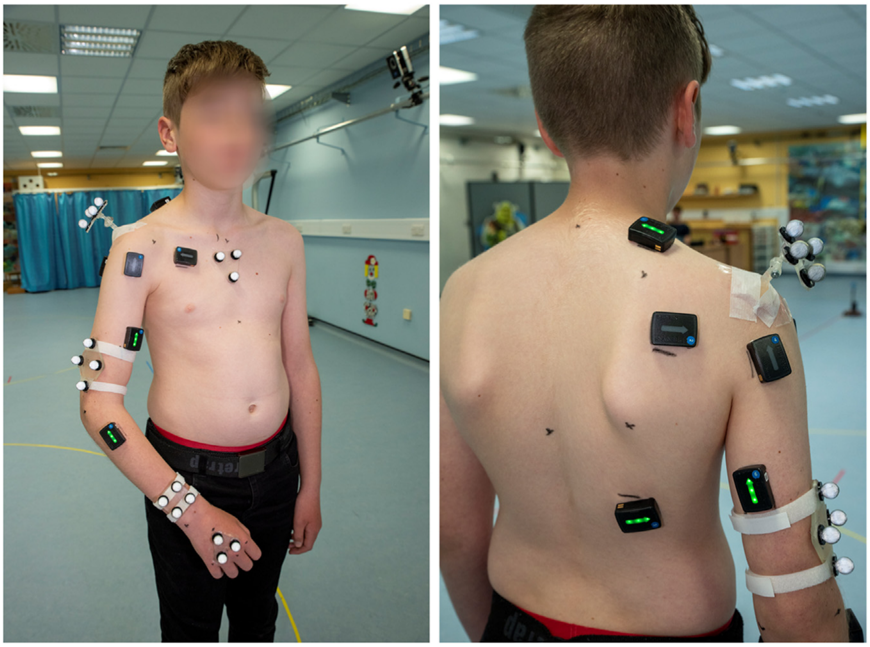

Figure 1 Overview of marker clusters and electromyograph electrode placement in study.

segments adapted from Jaspers et al[20,21] and van Andel et al[2] and available at https://doi.org/10.17638/datacat.liverpool.ac.uk/2386. sEMG electrodes were placed on the middle trapezius, infraspinatus, triceps, latissimus dorsi, deltoid (posterior and anterior), pectoralis major, biceps, wrist flexor, and extensor muscles according to SENIAM guidelines[13] and Criswell et al.[8] As a quality control check, used to ensure sufficient electrode placement, contact and adequate signal recording (including avoidance of unwanted noise), participants were instructed to carry out a single resisted movement against the assessor at a consistent submaximal intensity. Movements included shoulder elevation, shoulder lateral rotation, combined shoulder extension and adduction, shoulder push, elbow flexion, elbow extension, wrist extension, and wrist flexion. For subject calibration, the Pellenburg wand was used for virtual marker identification of the following bony landmarks: C7 spinous process (C7), T8 spinous process (T8), incisura jugularis (IJ), processus xiphoideus (PX), articulation sternoclavicularis (SC), articulation acromioclavicularis (AC), processus coracoideus (PC), trigonum scapulae (TS), angulus inferior (AI), angulus acromialis (AA), lateral epicondyle (LE), medial epicondyle (ME), radial styloid (RS), ulnar styloid (US), styloid process of third metacarpal (MC3), and distal heads of the second, third, and fifth metacarpophalangeal joints (MCP2, MCP3, and MCP5).[20-22]

Participants' movements were assessed in 4 unweighted movements (flexion, abduction, abduction to 45° with axial rotation [external and internal], and hand to back of head) and 3 self-selected weighted tasks of 0.5, 1.0, or 1.5 kg (flexion, abduction, and abduction to 45° with axial rotation), in that order. The movement protocol was informed by reviewing tasks assessed in similar studies, and movements evaluated during clinical assessments and discussions with clinicians who are experts in shoulder instability.[19,21,57] Movements were carried out in the same order for all participants to mitigate testing-order differences, which could confound results when interpreting differences observed in joint movements or muscle activity patterns. Participants were initially shown the movements by the assessor and then asked to carry them out to a count of 3 seconds up and 3 seconds down, mirroring the assessor who was positioned in front of them.

Data were collected at 100 Hz using a Vicon motion capture system (Vicon Motion Systems, Oxford, UK) (12 V5-Vantage motion analysis cameras, 2 synchronous coronal and sagittal video recordings, and Delsys Trigno electromyography system sampling at 2000 Hz [Delsys Inc., Natick, MA, USA]). Interpolation for any missing marker data was performed as appropriate using rigid body, pattern, and spline filling pipelines available within Vicon Nexus, version 2.12.1.[60]

Data processing and analysis

Joint angles were calculated using inverse kinematics and the Wu shoulder model[63] in Opensim, version 4.4.[9,52] Definitions of joint coordinate systems were consistent with International Society of Biomechanics (ISB) recommendations.[62] Model scaling and evaluation were consistent with best practice frameworks, that is, scaling ratios for each bone was estimated from selected marker pairs for each segment, obtained during the anatomical marker identification for static calibration and movement waveforms generated from inverse kinematics were reviewed (Supplementary Appendix S1).[14,52] Kinematics were smoothed using a Savitzky-Golay filter, with a window size of 99 and a polynomial order of 2.[63] The filter and parameters were selected as they perform well during high-frequency acceleration-time signals when compared to alternative methods, and based on our data set, performed the best for removal of noise while preserving the underlying signal.[50]

The glenohumeral joint origin was determined through geometrical scaling. This method was selected over regression, functional, or offset methods as the presence of excessive translation (instability) in this cohort would likely violate the assumptions required for implementation of the aforementioned methods. To reflect the angles observed by clinicians in practice, thoracohumeral and scapulothoracic angles were calculated for positions of the arm and scapula with respect to the thorax. Additionally, joint-specific angles for the glenohumeral, sternoclavicular, and acromioclavicular joints were calculated.

sEMG signals were band-pass filtered between 10 and 400 Hz using a second order Butterworth filter, and zero lag correction offset was then applied.[61] sEMG was normalized to the maximum encountered activation across any of the movement activities, including isolated movements against resistance for quality control, grip, and weighted and unweighted tasks.[37] No maximum voluntary contraction (MVC) testing was carried out to minimize risk of further instability during data collection and as this is known to be highly variable, particularly in pathologic populations.[55]

Group demographics are presented as frequencies. Statistical parametric mapping (SPM) with a Student *t* test was used to identify between-group differences for joint kinematics and normalized sEMG signals.[44] SPM allows for evaluation across the entire movement (sampling space) and accounts for the interconnected or bounded nature of the data. This avoids focus bias and data reduction, whereby only a limited number of points or summary metrics, which then become unbounded and are usually selected based on researcher preference, are selected for hypothesis testing.[44] Broadly, for each time point, SPM which is grounded in random field theory takes into consideration the differences and variability between waveform data points and identifies clusters where differences exist that are not due to a smooth random process. The additional advantages of this are that more realistic significance thresholds are achieved compared to multivariate methods such as Bonferroni corrections and multiple comparisons can be made.[44] Furthermore, interpretation of results is intuitive, as statistically significant differences are reflected with reference to the movement data, allowing identification of where in the movement cycle and how many differences (clusters) there were.[44] SPM with Student *t* test was used because the aim of our study was to evaluate if there are differences between 2 groups at the level of the impairment rather than on the basis of a theoretical classification system or etiologic subgroups.

For between-group comparisons, thoracohumeral and thoracoscapular angles were reported, to reflect the clinician's observation in practice, but were not included in the statistical analysis given that they are not physiologically representative and compliant with ISB recommendations or generated in the selected model. Differences of $\geq 10°$ were highlighted for between SI and CG group differences, as differences of this magnitude are likely apparent with clinical observation and larger than the error of measurement thresholds used in clinical movement analysis and our methodologies.[48,58] C3D files used for 3D movement and sEMG analysis are available at https://doi.org/10.17638/datacat.liverpool.ac.uk/2386.

Results

Group demographics

Data were collected for 30 young people, 15 with shoulder instability (SI group) and 15 sex- and age-matched controls (CG); the demographic data are presented in Table I.

SI group

For the SI group, 3 participants presented for data collection having sustained a first-time episode of shoulder instability and 12 after recurrent episodes of instability. The most common form of instability experienced prior to attendance was subluxation, reported by 13 participants. Only 1 participant reported having experienced a definite dislocation, and 1 participant was unsure if the most recent episode was a subluxation or dislocation. Ten participants had an atraumatic etiology, 4 reported a traumatic etiology, and 1 reported an ambiguous overlapping atraumatic or traumatic etiology. Two participants were unable to identify the direction of their instability. Subjective reports of anterior instability were reported by 7 participants, 2 reported posterior instability, 2 reported inferior instability, and 2 reported multidirectional instability in the posterior-inferior and anterior-inferior directions.

Length of time since last instability episode ranged from 4 hours to 32 weeks, with a mean time of 7 weeks (standard deviation 9 weeks). Two participants were unable to recall the length of time since their last episode. The number of self-reported subluxations ranged from 1 to >180, and the number of self-reported dislocations ranged from 1 to >90, with some participants and parents estimating the total number (subluxations and dislocations) by the product of the length of time since the onset of instability and a conservative daily frequency for instability episodes in cases of difficulties in recalling exact numbers.

Relevant past medical history

Two participants had formal diagnosis of connective tissue or hypermobility disorders. Of these, one had an atraumatic etiology and one had an ambiguous overlapping atraumatic and traumatic mechanism.

Joint kinematics

Mean range of motion values and 95% confidence intervals for all joint planes of movement and associated tasks are presented in Table II.

Mean between-group differences of 10° or more were observed most frequently in the glenohumeral rotation plane for the movements of both weighted and unweighted flexion and abduction. These results suggest that differences that are larger than errors of measurement may be observed at the glenohumeral joint rather than overall arm position (represented by the thoracohumeral movements). These differences were not apparent in combined movements.

Statistically significant between-group differences for kinematics in SI and CG are reported in Figure 2. An overview of all kinematic and sEMG SPM (*t*) graphs and *P* values are presented in Supplementary Appendix S2.

Table I Participant demographics for all study participants

	CG	SI
Age, yr	13.3 (3.1)	13.9 (2.9)
Height, cm	160.6 (16.8)	163.0 (15.7)
Weight, kg	52.4 (15.1)	56.6 (17.5)
Male/female, n	8:7	6:9
Beighton score, median (IQR)	2 (0.5-2.5)	6 (2-6.5)*
Grip strength: mean max value, left (kgf)	28 (12.5)	26.7 (10.5)
Grip strength: mean max value, right (kgf)	31.2 (13.6)	28.9 (10.4)
Dominant hand (L:R)	0:15	1:14
Participants whose nondominant hand was assessed for 3D, n	3 (L)	5 (L)†
Instability side, bilateral/left/right, n	N/A	10:1:4
Side assessed in 3D movement, L/R†, n	3:12	6:9
Weight selection for loaded tasks 0.5/1.0/1.5 kg, n	1:3:11	1:5:9

IQR, interquartile range; *3D*, 3-dimensional; *CG*, age- and sex-matched control group; *N/A*, not applicable; *SI*, shoulder instability group.
Unless otherwise noted, values are mean (SD).
* One participant was unable to do fifth digit (little) fingers because of previous injuries.
† Discrepancy due to dropouts for the side.

Three participants experienced episodes of shoulder instability (subluxations) during the abduction at 45° with axial rotation, weighted and unweighted tasks.

Statistically significant between-group differences were observed across almost all movement tasks and for all joint planes of movement. Consistent differences across the entire movement cycle and for all movement tasks were observed in the sternoclavicular protraction-retraction and elevation-depression planes. The SI group adopted a more protracted and elevated sternoclavicular joint during all movements. In most movements, this was accompanied by less internal rotation and upward tilt at the acromioclavicular joint. The SI group demonstrated less variability across the sternoclavicular and acromioclavicular joints. No differences were observed in the unweighted and weighted flexion tasks for the glenohumeral joint plane of elevation, and unweighted and weighted abduction to 45° with axial rotation at the acromioclavicular joint protraction-retraction plane. Statistically significant between-group differences for the measured sEMG in SI and CG are reported in Figure 3.

No statistically significant between-group differences were observed in the pectoralis major muscle in any of the movement tasks. Latissimus dorsi showed significant differences with decreased normalized activity across a greater proportion of tasks. Across all the muscles measured, weighted tasks had fewer muscle activity differences identified as being statistically significant between groups than unweighted tasks. Where differences were identified between groups, compared with the CG, the SI group had increased normalized activity of their middle trapezius, posterior deltoid, and biceps muscles whereas activity of their latissimus dorsi, triceps, and anterior deltoid were comparatively decreased. It appears that muscles that control scapular movement or have attachments on the posterior compartment of the body (middle trapezius and posterior deltoid) have higher normalized activity whereas muscles that primarily control humeral movement have lower normalized activity (latissimus dorsi and triceps). However, the inverse is true for muscles on the anterior portion of the body with increased biceps and decreased anterior deltoid activity.

Discussion

The aim of this study was to identify if there are any movement and muscle activity differences between young people with shoulder instability and age- and sex-matched controls and quantify these differences where they exist. Fundamental research evaluating mechanisms for shoulder instability in young people is very limited, and our cohort is one of the youngest evaluated.[4,19,42,57] Our study provides evidence that following an episode of instability, there are muscle activity and movement pattern differences between those with shoulder instability and age- and sex-matched controls. Using the protocol developed, it has been possible to quantify the variability in upper-limb movements. These data may help future research identify meaningful differences or changes in muscle activity or joint kinematics between young people with and without shoulder instability. It has also been possible to identify between-group differences, considered statistically significant, across several muscles, joint planes of movement, and phases in the movement cycle.

Overall thoracohumeral angles, and by proxy arm positions, during the movements were similar between groups; however, the SI group adopted different movement

Table II ROM values for planes of movement across all joints and movement tasks for the SI and CG (degrees)

Motion	Flexion		Flexion with weight		Abduction		Abduction weight		Abduction at 45° with axial rotation		Abduction to 45° with axial rotation and weight		Hand to back of head	
Group	SI	CG	SI	CG	SI	CG	SI	CG	SI	CG	SI	CG	SI	CG
TH elevation plane	92 (81, 102)	94 (86, 102)	92 (82, 102)	97 (86, 107)	107 (89, 124)	98 (83, 113)	104 (89, 120)*	94 (78, 109)*	23 (17, 28)	23 (19, 28)	23 (17, 29)	25 (19, 30)	97 (78, 117)	92 (77, 107)
TH elevation angle	133 (122, 144)	130 (125, 134)	136 (126, 147)	134 (130, 138)	137 (127, 147)	132 (128, 135)	138 (127, 150)	133 (130, 136)	16 (13, 20)	17 (13, 21)	21 (16, 25)	19 (15, 23)	116 (107, 125)	113 (107, 120)
TH rotation	100 (87, 113)	99 (90, 108)	98 (90, 106)	103 (92, 115)	107 (89, 125)	99 (85, 114)	102 (86, 117)	98 (85, 111)	94 (87, 101)	97 (92, 103)	95 (88, 102)	96 (89, 103)	105 (95, 115)	106 (97, 116)
ST protraction	25 (21, 29)	24 (21, 27)	28 (23, 33)	27 (24, 29)	18 (12, 24)	17 (13, 21)	20 (15, 24)	18 (15, 20)	11 (8, 14)	11 (9, 13)	14 (10, 18)	15 (12, 17)	17 (11, 22)	17 (13, 20)
ST rotation	39 (37, 42)	40 (40, 44)	45 (42, 47)	43 (39, 48)	40 (36, 43)	42 (37, 48)	44 (40, 47)	46 (41, 52)	12 (10, 15)	12 (9, 15)	16 (13, 18)	15 (11, 18)	34 (31, 37)	37 (34, 41)
ST tilt	29 (23, 36)	33 (27, 38)	32 (26, 39)	37 (31, 43)	21.7 (16.1, 27.3)	23 (19, 28)	19 (15, 24)	20 (15, 25)	11 (9, 13)	8 (7, 10)	15 (12, 17)	13 (10, 15)	23 (19, 28)	25 (20, 29)
GHJ elevation plane	74 (63, 85)	74 (66, 81)	70 (61, 78)*	80 (68, 92)*	58 (45, 70)	58 (53, 63)	54 (38, 69)	54 (47, 60)	15 (10, 20)	14 (11, 17)	14 (8, 19)	19 (10, 27)	56 (39, 73)	54 (45, 63)
GHJ elevation angle	101 (89, 112)*	91 (87, 96)*	99 (89, 110)	94 (89, 98)	105 (95, 115)	98 (93, 103)	104 (93, 116)	96 (92, 100)	14 (11, 18)	15 (13, 17)	17 (13, 20)	16 (13, 18)	86 (75, 98)	81 (76, 86)
GHJ rotation	89 (79, 99)*	100 (92, 108)*	87 (79, 96)*	102 (92, 112)*	60 (49, 70)*	70 (60, 81)*	57 (44, 70)*	67 (58, 75)*	94 (85, 102)	86 (79, 92)	92 (84, 100)	87 (79, 94)	93 (84, 103)	98 (88, 108)
ACJ protraction	32 (25, 39)	34 (29, 39)	36 (29, 42)	37 (30, 43)	32 (27, 38)	35 (30, 39)	32 (25, 39)	34 (28, 39)	10 (9, 12)	9 (7, 11)	14 (12, 17)	14 (11, 17)	30 (23, 36)	34 (27, 41)
ACJ rotation	16 (13, 20)	17 (14, 19)	17 (15, 20)	18 (15, 20)	17 (13, 21)	15 (13, 18)	17 (14, 20)	14 (12, 16)	9 (8, 11)	9 (7, 10)	11 (9, 13)	9 (8, 10)	14 (11, 18)	14 (11, 17)
ACJ tilt	31 (28, 34)	32 (28, 36)	33 (30, 36)	33 (29, 37)	28 (25, 32)	29 (23, 34)	29 (26, 32)	31 (28, 36)	7 (6, 9)	7 (6, 9)	9 (8, 11)	9 (7, 11)	24 (22, 26)	26 (22, 29)
SCJ protraction	25 (20, 29)	24 (21, 27)	27 (23, 31)	26 (24, 29)	25 (22, 29)	25 (22, 28)	27 (23, 30)	27 (24, 30)	7 (5, 8)	6 (5, 8)	10 (8, 12)	10 (7, 12)	20 (17, 23)	22 (19, 25)
SCJ elevation	11 (10, 12)	11 (10, 12)	13 (12, 15)	13 (12, 14)	12 (10, 13)	12 (11, 14)	14 (13, 16)	15 (13, 16)	5 (4, 6)	6 (5, 7)	7 (6, 8)	8 (6, 9)	10 (9, 11)	11 (10, 12)

ROM, range of motion; *TH*, thoracohumeral; *ST*, scapulothoracic; *GHJ*, glenohumeral joint; *ACJ*, acromioclavicular joint; *SCJ*, sternoclavicular joint; *SI*, shoulder instability group; *CG*, age- and sex-matched control group.

Values are mean and 95% confidence intervals.

* Between-group differences ≥10°.

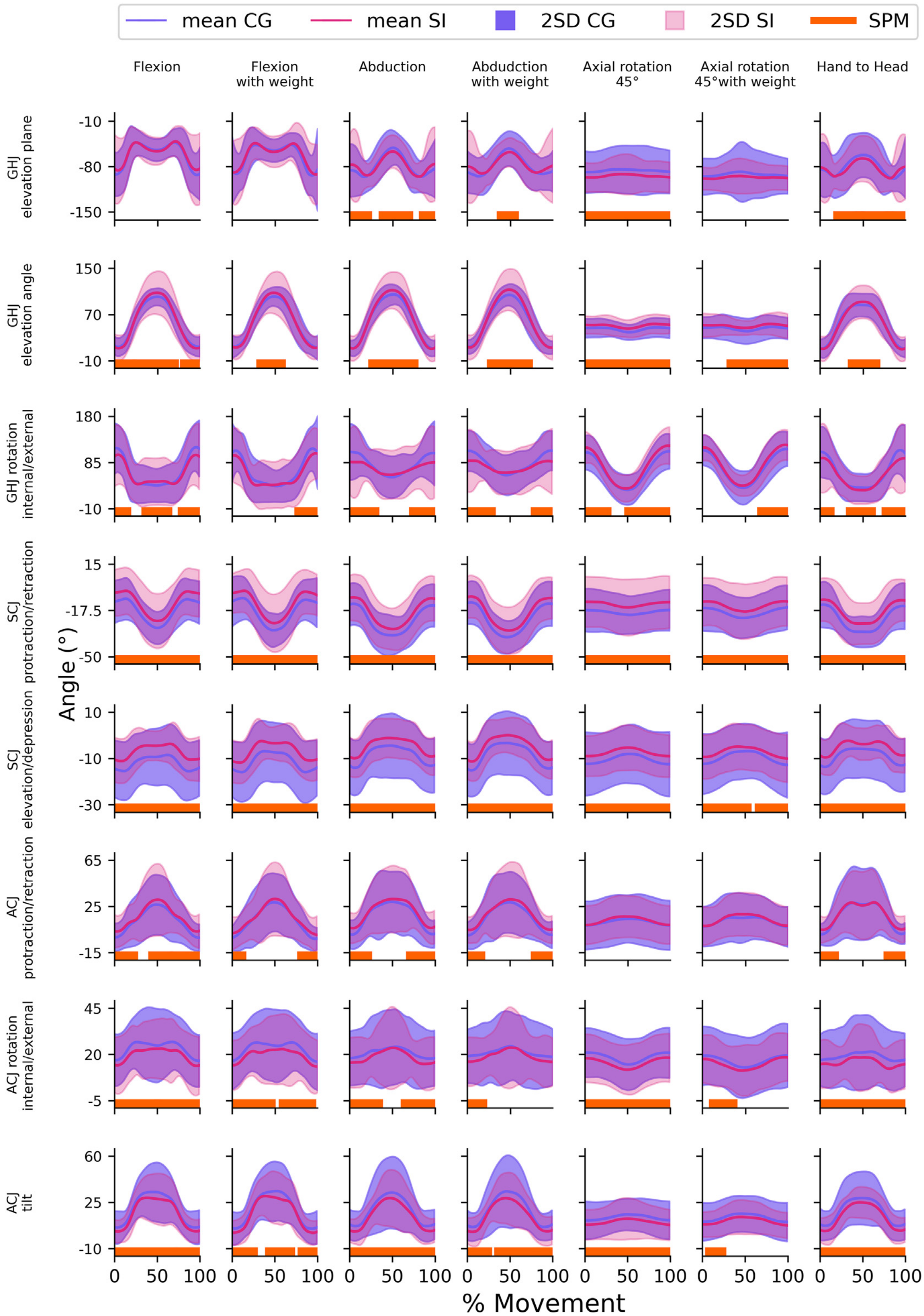

Figure 2 SI and CG kinematics for all movements and SPM. Joint angles for all joints and all movements. Lines show mean group angles, shaded areas indicate the 2SD, and the orange bars on the horizontal axis highlight regions of statistically significant difference between groups using SPM. Column headings: *Flexion*, flexion with weight; *Abduction*, abduction with weight; *Axial rotation 45°*, abduction at 45° with axial rotation; *Axial rotation 45°*, abduction to 45° with axial rotation and weight; *Hand to head*, hand to back of head. *SI*, shoulder instability group; *CG*, age- and sex-matched control group; *SPM*, statistical parametric mapping; *GHJ*, glenohumeral joint; *SCJ*, sternoclavicular joint; *ACJ*, acromioclavicular joint; *2SD*, 2 standard deviations.

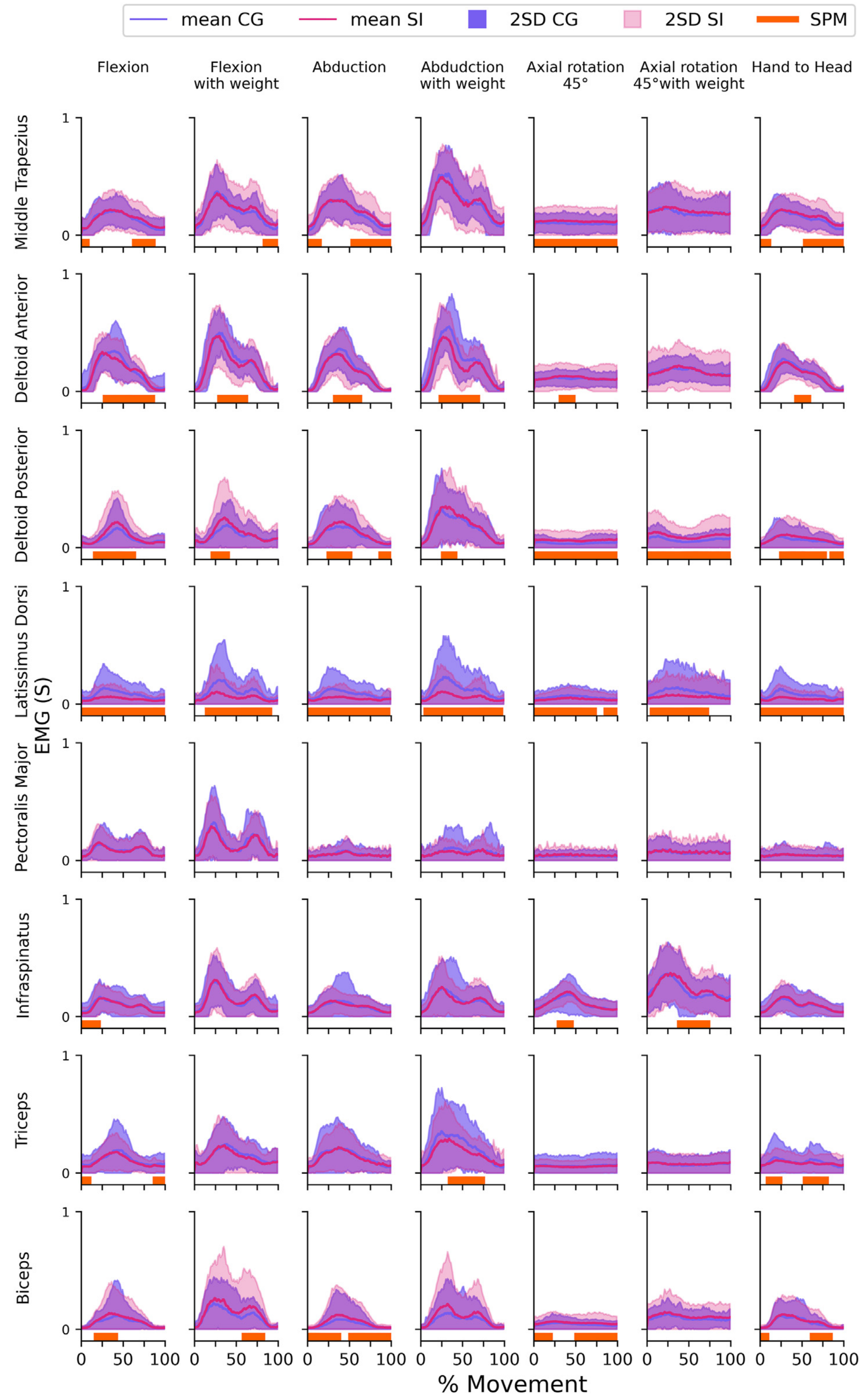

Figure 3 SI and CG surface EMG for all movements and SPM. Muscle activity profiles for all muscles and all movements. Lines show mean group angles, shaded areas indicate the 2SD, and the orange bars on the horizontal axis highlight regions of statistically significant difference between groups using SPM. Column headings: *Flexion*, flexion with weight; *Abduction*, abduction with weight; *Axial rotation 45*°, abduction at 45° with axial rotation; *Axial rotation 45*°, abduction to 45° with axial rotation and weight; *Hand to head*, hand to back of head. *SI*, shoulder instability group; *CG*, age- and sex-matched control group; EMG, electromyography; *SPM*, statistical parametric mapping.

strategies across the shoulder girdle joints to achieve this, mainly at the sternoclavicular and acromioclavicular joints. The joint planes of movement and periods of the movement cycle identified as having statistically significant differences varied according to the movement being carried out, although some behaviors were common to the SI group. Consistent differences were seen for all movements and across the entire movement cycle at the sternoclavicular joint, with the SI group adopting a more protracted and elevated sternoclavicular joint during the movements. In most movements, this was accompanied by less internal rotation and upward tilt at the acromioclavicular joint. Common differences in behavior were also seen in the sEMG measurements of the SI group. Direct comparison of our findings to other studies is challenging because of variations in the movements conducted, number and selection of segments and muscles measured, and methods of analysis used for joint kinematics and sEMG. However, where methods are generally comparable, our results are similar for the anterior deltoid, infraspinatus, and triceps muscles, which had higher normalized activity profiles in the SI group.[17,16,56,57] Biceps was identified as having higher levels of normalized activity in the SI group, which is different from other published studies, which reported lower levels of normalized activity.[17,16,57] Differences in our results may reflect the fact that although movements between studies were broadly similar, they were not identical. As a result of the impairment, the observed movement and muscle activity patterns of those with shoulder instability may be constraining movements around the shoulder girdle to maximize stability of the glenohumeral joint.

Pectoralis major activity was not identified as being statistically significantly different between groups for any of the movements assessed. This may be unexpected as it is often assumed to be a driver for anterior and possibly multidirectional instability given its action on the humerus. Instability may occur under different task or environmental constraints not evaluated in our study.[54] Development of movement protocols that encapsulate all possible scenarios in which instability may occur is challenging and highlights the challenges of developing a universal protocol for assessing impairments in the upper limb. Further work will be needed to explore how the testing protocol can be extended to match with different subgroups or pathophysiologic presentations. Future research may customize protocols on the basis of clinical signs or a form of baseline screening. Furthermore, our study aimed to identify differences related to instability at a group rather than an individual level, and the overall number of instability episodes within a movement task were also relatively low compared with the overall number of repetitions. Although these methods of measurement can be used to inform clinical decision making on an individual basis, further work is needed to evaluate the prognostic and clinical utility of derived 3D and sEMG data for informing decision making within shoulder instability.[3,27,46,47,52]

Within existing instability classification systems and accompanying treatment philosophies, it is not clear if the observed movements and muscle activity develop in response to the impairment or are a significant contributing factor to its development.[12,30,45] Several treatment philosophies have developed that seek to make use of the ‘‘kinetic chain,’’ ‘‘activating the cuff,’’ cocontraction, or redundancy principles. Although these principles seem intuitive, they remain conceptual and effectiveness has not yet been demonstrated. Unpicking the relevance of the identified muscle activity profiles and movement patterns is challenging in young people given that their neuromusculoskeletal system is continually developing alongside possible changes to their environment (home and school life) and personal factors.[59] These developments are often overlaid with changes to body structure, body functions, and personal factors that contribute to the impairment of instability.[59] Furthermore, there are limited longitudinal natural history 3D kinematic and muscle activity data and an absence of comparative data pre and post the occurrence of an initial instability episode. We propose that the observed differences are resultant from the SI group optimizing their muscle activity and movement patterns for stability in response to any underlying changes in their perceptual motor control strategies, bony or soft tissue structures in their shoulder.[54] When comparing the weighted and unweighted tasks, there were fewer differences between the SI and CG groups for both kinematics and sEMG measures during the weighted tasks. Under loaded or novel conditions, the CG may also have constrained their movements for stability. Therefore, it appears that in young people whose joint stability is challenged they will constrain movements around the shoulder girdle but may transition to more variable movement patterns as their ability to maintain stability is improved, subsequently increasing the degrees of freedom available and using the passive forces of the soft tissues.[54] This is consistent with existing motor control paradigms and experimental studies but further work investigating indices of stability are needed to evaluate this.[1,35,54] This has implications for rehabilitation as it demonstrates there is no universally ideal or normative movement pattern and clinicians should avoid trying to impose assumed ‘‘best-movement patterns’’ on those undergoing rehabilitation. It may also explain why existing treatment approaches that integrate early weight-bearing or loading have positive results. The applied load may constrain the task, effectively reducing the degrees of freedom and requiring increased muscle cocontraction, naturally leading to increased glenohumeral joint stability.[5,31]

Our results demonstrate that assessment of an upper limb using 3D movement analysis and sEMG can produce large amounts of data for a limited number of tasks. Measurement and assessment of all movement features is complex, and existing methods of clinical assessment may not capture this complexity. Being able to accurately measure the differences and changes observed in a reliable way without technology is unlikely given the large number and magnitude of differences seen within and between movements. Differences in joint planes of movement and muscle activity was dependent on the movement task being carried out. The assessment of a single movement may therefore not be sufficient for identifying links between the impairment of interest and associated biomechanical data needed to inform clinical decision making. This is consistent with studies investigating 3D upper limb function in other populations.[6,47] However, within shoulder instability, it is not clear which movement tasks and generated biomechanical data are the most important for informing decision making. Selection of tasks for evaluation with 3D movement analysis and sEMG needs to be considered alongside the large volume of data that is generated using these methods, which can limit interpretability and translation into clinical practice.

Limitations

Although our protocol was able to identify differences in the joint movements and muscle activity patterns of those with shoulder instability, this was done in a limited number of movements and superficial muscles. Although sEMG does not allow for direct measurement of deeper glenohumeral or scapular stabilizing muscles, for example, the rotator cuff group or serratus anterior, sEMG is preferable for use in young people and children for ethical and pragmatic reasons given that it is noninvasive with fewer risks. Musculoskeletal modeling tools may be used to approximate information about muscles that are challenging to measure and provide some further understanding of their role.[9,52] Although the movements used for normalization of sEMG were consistent across most participants, it is recognized that in some cases, there was variation in the movements and associated values used. There is no universally agreed method for normalization or interpretation of sEMG, particularly in those with pathology, and further work is needed to develop consistent practice and evaluate the impact of different normalization methods on decision making in clinical practice.[37,47,53] sEMG can be affected by cross-talk, although appropriate placement according to established guidelines, trained experts, and quality control checks as carried out in our study can mitigate against this.

During the protocol, participants carried out movements over a large range of motion. Calculation of joint angles, mainly at the glenohumeral joint, at the extremes of motion can result in a number of mathematically correct but clinically counterintuitive solutions given that differentiation of the planes of movement can be challenging. Calculation of joint kinematics was performed using established modeling conventions, but interpretation of kinematic results should be carried out with this understanding. In our study, we chose to group participants at the level of the impairment as there is limited fundamental science demonstrating proposed mechanisms and existing classification systems are conceptual and can be nondiscriminatory or prone to misclassification.[25,38,45] Further subgroup analysis informed by existing classification frameworks and traumatic or atraumatic etiology may be carried out in future work. However, a fundamental step is to ensure that categories are developed on the basis of appropriate measures or first principles and that the underlying pathology is not confused with the impairment.[11]

Our study only conducted measurements at a single time point in young people aged between 8 and 18 years. Further longitudinal measures in a larger sample with a wider range of ages (young people and adults) and etiological subgroups is required for a robust understanding of factors that contribute to shoulder instability. Future research may also include other biopsychosocial factors relevant to shoulder instability. It is possible that the differences observed between groups may be influenced by the order, number of repetitions, and speeds of movement in our protocol, that is, several unweighted movement repetitions progressing to weighted repetitions. Variation in any components of the protocol may potentially result in different outcomes. This includes selection of start and end points for segmenting movements, which may influence analysis with SPM, although segmentation was consistent within our study. It is recognized that the weights used in our study were relatively low and individuals may have been working at different levels of their maximum capacity. Given the exploratory nature of the study and ethical considerations to minimize risk of harm, weight selection was a pragmatic choice. Additionally, only participants who were able to engage with the entire measurement protocol were included. Our selected protocol may not be feasible in patients with more severe forms of instability. Despite this, our protocol was able to measure the impairment of interest, which usually occurred in the abduction at 45° and axial rotation tasks (weighted and unweighted), a position known to challenge the stability of the glenohumeral joint and occurred toward the end of the movements being assessed.

During the clinical assessment, the number of self-reported instability episodes was high when compared to other studies and likely subject to recall bias, evidenced by some participants and their parents being unable to recall a definitive number or features and timelines related to the instability.[15,28,29,33] Existing studies recognize that the true incidence and prevalence of shoulder instability is likely under-reported and the true long-term health and economic impact of recurrent instability, particularly subluxations, is unknown.[7,26,29] Young people classified as having atraumatic instability can experience multiple episodes that do not interfere with overall function and sometimes experience a delayed presentation to health care professionals owing to a combination of absence of knowledge regarding their condition and dependency on parents for accessing health services.[15,28,29,33] Further research should evaluate the true economic and health care costs for recurrent shoulder instability, facilitated by improved methods of long-term follow-up and recording of instability episodes, and its link to long-term health outcomes.

Conclusion

Young people with shoulder instability have consistent differences in their muscle activity and movement patterns when compared to age- and sex-matched controls. Consistently observed differences at the shoulder girdle included increased sternoclavicular protraction and elevation accompanied by increased normalized activity of the posterior scapula stabilizing muscles and decreased activity of the posterior humeral mobilizing muscles. Young people with shoulder instability demonstrated less variability in their overall movements and were likely constraining their movements to minimize glenohumeral instability. Existing methods of measurement may be used to inform clinical decision making; however, further work is needed to evaluate the prognostic and clinical utility of derived 3D and sEMG data for informing decision making within shoulder instability and associated subgroups.

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Supplementary Data

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