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Shoulder kinematics during the wall push-up plus exercise

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Background and hypothesis: The push-up plus exercise is a common therapeutic exercise for improving shoulder function and treating shoulder pathology. To date, the kinematics of the push-up plus exercise have not been studied. Our hypothesis was that the wall push-up plus exercise would demonstrate increased scapular internal rotation and increased humeral anterior translation during the plus phase of the exercise, thereby potentially impacting the subacromial space.
Methods: Bone pins were inserted in the humerus and scapula in 12 healthy volunteers with no history of shoulder pathology. In vivo motion during the wall push-up plus exercise was tracked using an electromagnetic tracking system.
Results: During the wall push-up plus exercise, from a starting position to the push-up plus position, there was a significant increase in scapular downward rotation ($P < .05$) and internal rotation ($P < .05$). The pattern of glenohumeral motion was humeral elevation ($P < .05$) and movement anterior to the scapular plane ($P < .05$), with humeral external rotation remaining relatively constant.
Conclusion: We found that during a wall push-up plus exercise in healthy volunteers, the scapula was placed in a position potentially associated with shoulder impingement. Because of the shoulder kinematics of the wall push-up plus exercise, utilization of this exercise without modification early on in shoulder rehabilitation, especially in patients with subacromial impingement, should be considered cautiously.
Level of evidence: Laboratory study.

Shoulder pain is one of the most common musculoskeletal complaints of patients seeking medical care.[14,20] Shoulder pathologies such as impingement, instability, and rotator cuff tears have been associated with abnormal shoulder kinematics, especially abnormal scapular kinematics.[15,16,19,21,27,31,33] Normal scapular movement during humeral elevation consists of upward rotation, internal rotation for some planes and angles of elevation and external rotation for other planes and angles of elevation, as well as posterior tilting of the scapula on the thorax.[16,18,19,22] It is believed that normal scapular kinematics are essential to maximize the volume of the

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subacromial space during arm elevation and avoid impingement of the rotator cuff either externally or internally.[13,23]

The scapulothoracic musculature is critical to providing both motion and stability to the shoulder girdle complex to allow for proper function of the glenohumeral joint.[3,10,16] In particular, the serratus anterior muscle can contribute to scapular upward rotation, external rotation, and posterior tilting during arm elevation. Furthermore, the serratus anterior acts to stabilize the medial border and inferior angle of the scapula against the thorax to prevent scapular ''winging'' during arm elevation. Decreased serratus anterior muscle function has been observed in patients with shoulder pathology.[3,16,29]

Thus, exercises focusing on restoring scapular mobility and stability are an important part of the rehabilitation of nonoperative and postoperative patients with shoulder pathologies.[2,4,25] Because of its critical functional role, the serratus anterior muscle is a component of many therapeutic exercise protocols.

The push-up plus exercise is a modification of a standard push-up exercise, where the subject performs maximal scapular protraction once the elbows are extended. Push-up plus exercises have been advocated for use in shoulder rehabilitation programs, because this exercise has been shown to elicit high serratus anterior muscle activity[5,9,17] in combination with relatively low upper trapezius activity.[17] A low upper trapezius activity to serratus anterior activity ratio may be desirable because increased upper trapezius activity combined with decreased serratus anterior activity has been reported in subjects with shoulder pain.[13,16,28] Furthermore, imbalances in serratus anterior and upper trapezius activity may result in decreased scapular upward rotation and posterior tilting during humeral elevation.[16] Thus, the push-up plus exercise can be considered in the planning of therapeutic exercise approaches aimed at correcting scapular kinematics in patients with shoulder pathology.

Alternatively, the scapular protraction that is occurring through clavicular protraction during the plus phase of the push-up plus exercise may be disadvantageous to the subacromial space, thus negatively impacting the rotator cuff tendons. Increased scapular protraction has been demonstrated to reduce the acromiohumeral distance.[30] In addition, if anterior translation of the humeral head occurred during this plus phase, this might result in increased risk for impingement of the rotator cuff tendons beneath the coracoacromial ligament. Although studies demonstrating high activation of the serratus muscle are important to consider in exercise selection, it is also important to know how the kinematics of the exercise are impacting the glenohumeral joint.

The push-up plus exercise is often modified from a standard push-up plus to be performed against a wall in the early stages of shoulder rehabilitation to limit the amount of weight-bearing during the exercise. The wall push-up plus exercise has been demonstrated to elicit serratus anterior activity at moderate to high levels comparable to other exercises aimed at strengthening the serratus anterior at 90° of humeral elevation.[9,17] However, to our knowledge, shoulder kinematics during the push-up plus exercise have yet to be investigated. Therefore, the purpose of this study was to describe shoulder kinematics during the wall push-up plus exercise. Our hypothesis was that the wall push-up plus exercise would demonstrate increased scapular internal rotation and increased humeral anterior translation during the plus phase of the exercise as compared to the starting position, potentially impacting the subacromial space.

Materials and methods

Subjects

This study was approved by the Institutional Review Board at the University of Minnesota. Twelve subjects (7 males, 5 females) participated in the study and were part of a larger on-going study.[18] Their mean age was 29.3 years (+/- 6.8 years), mean height was 173.6 cm (+/- 8.12 cm), and mean weight was 77.5 Kg (+/- 13.8 Kg). Eleven of the subjects were right hand dominant and the non-dominant shoulder was tested in all but two subjects, who elected to have their dominant shoulder tested. As a result 3 right shoulders and 9 left shoulders were tested.

Instrumentation

Motion testing was conducted using the Flock of Birds mini-bird electromagnetic tracking sensors (Ascension Technology Corporation, Burlington, VT) and associated Motion Monitor software (Innovative Sports Training, Chicago, IL) which allowed for simultaneous tracking of up to seven sensors at a sampling rate of 100 Hz per sensor. Static accuracy for the mini-bird sensors has been reported at 1.8 mm and 0.5° (Ascension Technology Corporation, Burlington, VT). Milne et al[24] reported an optimal operational range of 22.5-64.0 cm, a mean rotational error of 1.6% of the rotational increment, and accuracy of $<1°$ for similar DC tracking devices.[24] One sensor was attached to a digitizing stylus and tip offsets were determined in the lab to have a root mean square (RMS) accuracy of less than 1 mm using a custom calibration grid.

Procedures

Threaded 2.5-mm pins which engaged the far cortex were placed under sterile conditions by an orthopaedic surgeon (RFL) for in vivo tracking of each subject's scapula and humerus.[18] Subjects were given oral prophylactic antibiotics and local anesthetic prior to the surgical procedure. To account for skin motion during testing, skin incisions were of adequate length (1-2 cm) to allow unfettered movement of the humerus and scapula during arm motion. Pin placement was in the lateral spine of the scapula at the acromial base and just distal to the deltoid attachment on the lateral humerus. One pin was placed per segment and insertion locations allowed direct placement into bone without passing through any muscle or tendinous tissue. Pin placement was verified using fluoroscopy. Sensors were rigidly secured to the pins via sensor housings, with an additional sensor taped to the thorax below the sternal notch to record thoracic position.

Local coordinate systems were identified for each segment through the digitizing of anatomical landmarks to align axes following International Society of Biomechanics (ISB) recommended protocols and landmarks.[32] These landmarks included the sternal notch, xiphoid process, spinous process of C7 and T8 for the thorax, the root of the scapular spine, inferior angle and posterolateral acromion for the scapula, and medial and lateral epicondyles for the humerus.[32] Estimation of the center of the humeral head was determined by rotating the arm passively to over 10 different positions.[1]

Kinematic motion testing was completed for each subject performing the push-up plus exercise against a wall. Subjects stood at approximately 1.5 times their arm length from the wall, with palms against the wall at the level of the shoulders to standardize the initial position, beginning the exercise leaning forward with their chest near the wall (Figure 1, *A*). The subjects were then asked to perform the push-up plus exercise by extending the elbows and pushing out from the wall (Figure 1, *B*). When the arms were fully extended, they were instructed to further protract the shoulders performing the ‘‘plus’’ phase, and then return to the initial position. Subjects performed 1 to 2 trials of the exercise at a comfortable self-selected speed. Pain ratings on a self-reported 0-10 scale were monitored throughout the testing. Pins, housings, and sensors were monitored for rigidity before removal at the end of the test session.

Subjects were given acetaminophen and ice for post-procedure pain control. Incision sites were closed using nylon sutures or adhesive strips. Follow-up on each subject’s level of function and pain for the following 2 days occurred by phone with an in-person examination 7-10 days post-testing.

Data analysis

The wall push-up plus exercise was divided into four events. Event 1 was the starting position with the trunk closest to the wall (Figure 1, *A*). Event 2 was the end of the traditional push-up and beginning of the plus phase (Figure 1, *B*), manually identified as the point of the graph where the slope of humerothoracic plane of elevation changed (Figure 2). Event 3 was the end of the plus event being at the point of maximum scapular protraction, identified at the point of the graph of peak humeral plane of elevation (Figure 2). Event 4 was the end position with the trunk returning to closest proximity to the wall (Figure 1, *A*). Events were differentiated in the Motion Monitor program by using cut-off points on the graph of humeral plane of elevation (Figure 2). Descriptive statistics were averaged during the push up plus exercise across subjects (mean, standard deviation, standard error) for all 8 dependent variables (scapular: upward/downward rotation, internal/external rotation, and anterior/posterior tilting; glenohumeral: plane of elevation, elevation angle, and axial rotation; glenohumeral translation: anterior-posterior and superior-inferior) (Figure 3). For ease of clinical interpretation left side data was converted to right side equivalency and mean values were multiplied by -1 for scapular upward rotation and glenohumeral elevation and external rotation. Glenohumeral translation was described relative to the starting position (event 1). Normality was verified by testing skewness and kurtosis on each dependent variable for each phase of the wall push-up plus exercise.[8] Normality was accepted for all dependent variables, such that parametric statistics were appropriate for further analysis.

To determine if differences in scapular and humeral rotations occurred across events, repeated measures ANOVAs were performed with the wall push-up plus event as the factor (1, 2, 3, and 4). Pairwise comparisons were performed for event 1 to events 2-4. In the presence of a significant main effect, a Tukey-Kramer follow-up was completed for each pairwise comparison. For translation values, repeated measures ANOVAs compared across events 2-4. Statistical significance was chosen for $P < .05$. All analyses were completed using the NCSS 2000 statistical software (Number Crunching Statistical Systems, Kaysville, Utah).

Results

Subjects reported a mean pain rating of 1.1/10 on a numeric pain scale during the wall push-up plus exercise. There were no follow-up complications related to pin placement. Mean scapular kinematics (in degrees) for internal rotation, upward rotation, and posterior tilting with standard deviation values are presented in Table I. Descriptive data across events of the wall push-up plus exercise are presented in Figures 4 and 5.

The initial position of the scapula was internal rotation, upward rotation and anterior tilting (event 1, Table I) becoming significantly more internally rotated ($P < .05$) and less upwardly rotated ($P < .05$) during the push-up (event 2) and push-up plus (event 3) events. At the completion of the exercise (event 4), the scapular position returned to a position similar to the starting position. There was no significant change in angular position for scapular tilting during the wall push-up exercise (Table I).

The initial glenohumeral position was elevation and external rotation, posterior to the scapular plane, becoming significantly more elevated ($P < .05$, Figure 4, *A*) and more anterior to the scapular plane ($P < .05$, Figure 4, *B*) during the push-up and push-up plus events. At the completion of the exercise (event 4), the glenohumeral positions returned to positions similar to the starting position. There was no significant change in humeral external rotation angular positioning during the wall push-up exercise (Figure 4, *C*).

The pattern of glenohumeral translation from the starting position to the end of the plus event was to appear to translate anteriorly with a return to a position similar to the starting position at end position. However, no significant differences across events were found during the wall-push up exercise for either anterior/posterior or superior/inferior glenohumeral translation (Figure 5).

Discussion

When shoulder pathologies lead to poor scapular control, the push-up plus exercise can be a frequent addition to a rehabilitation program. Rationale for this choice has been

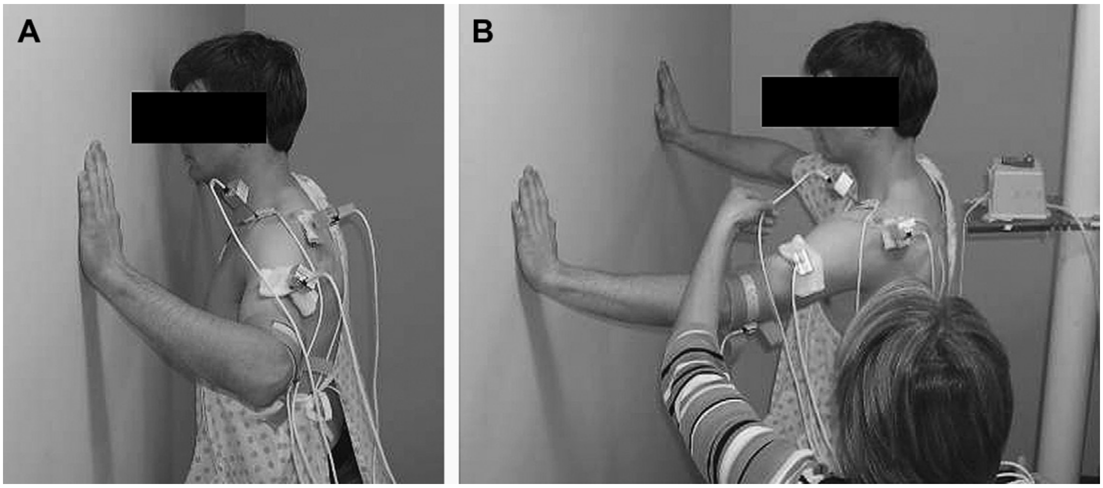

Figure 1 Wall push-up plus (A) starting and ending position (events 1 and 4); and (B) push-up position (event 2).

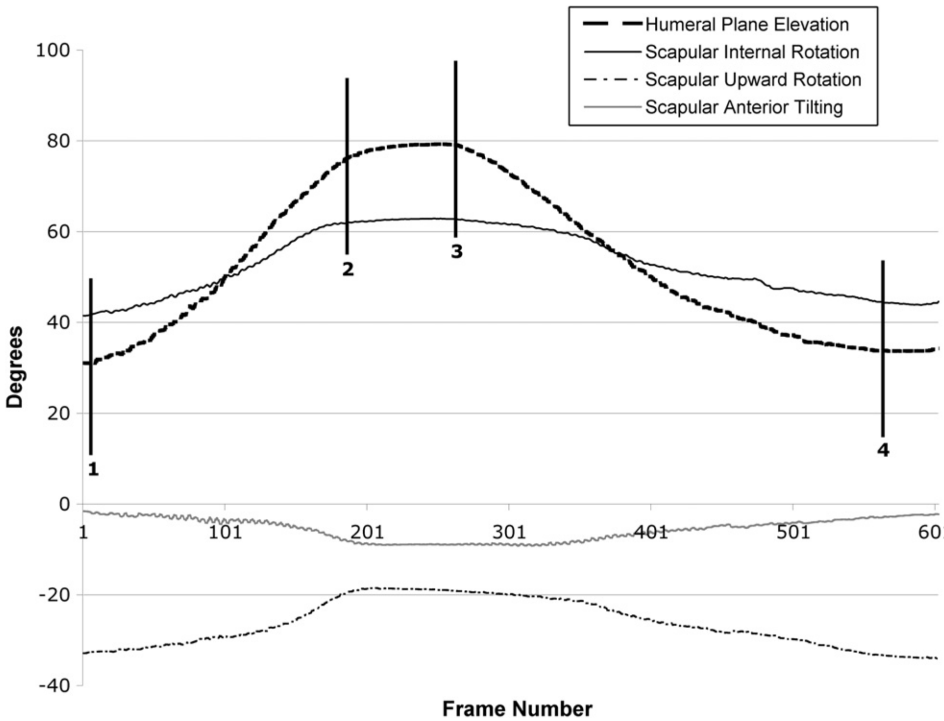

Figure 2 Continuous data during 1 repetition of the wall push-up plus. Scapular internal/external rotation (___); upward/downward rotation (_._.); anterior/posterior tilting (___). Humeral plane of elevation (- - -) with event markers: 1 = starting position, 2 = push-up, 3 = push-up plus, 4 = end position.

based on high activation of this muscle during the exercise, combined with low upper trapezius activation, without any knowledge of how the exercise affects scapular or glenohumeral kinematics. Using bone-fixed electromagnetic tracking, we found that during the wall push-up plus exercise, there was significant internal rotation and downward rotation of the scapula. Additionally, we found that there was increased plane of elevation and increased glenohumeral elevation, with glenohumeral external rotation remaining relatively constant from the starting position to the push-up plus event. Scapulothoracic and glenohumeral motion patterns observed during the wall push-up plus exercises lead to a position that may result in a decreased volume of the subacromial space or internal impingement of the rotator cuff undersurface.

The aim of the push-up plus exercise is to strengthen the serratus anterior muscles, while minimizing upper trapezius muscle activation.[17] The serratus anterior is an important

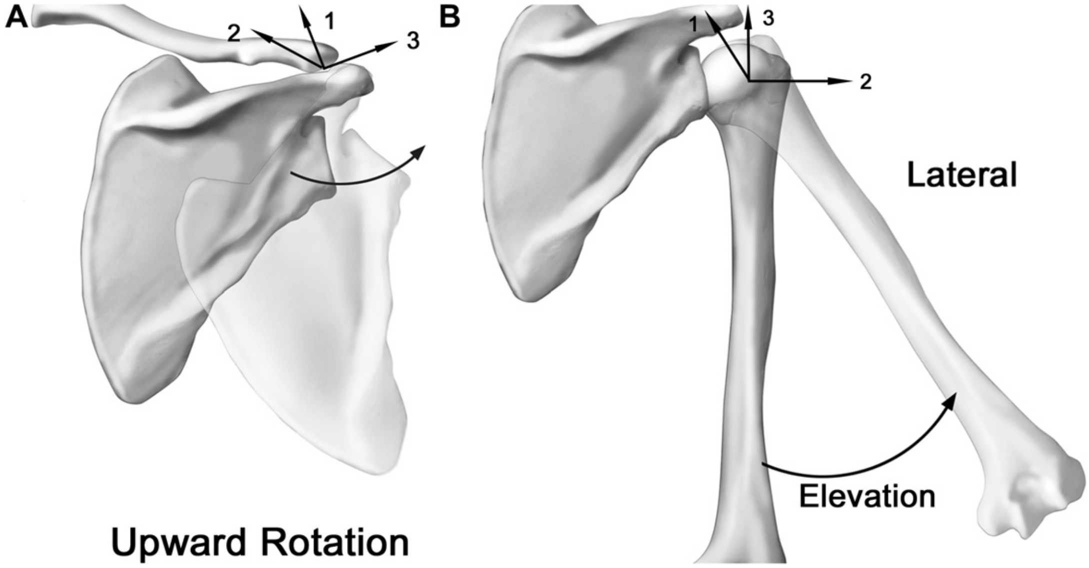

Figure 3 Schematic of coordinate systems for scapula (A) and humerus (B). Scapular internal/external rotation occurs about the 1st vertically oriented axis, upward/downward rotation about the 2nd axis perpendicular to the scapular plane, and anterior/posterior titling about the 3rd axis. Humeral elevation occurs about the 1st anteriorly directed axis, plane of elevation about the 2nd initially laterally directed axis, and internal/external rotation about the 3rd vertically oriented long axis.

Table I Scapular kinematics during the wall push-up plus exercise (N = 12)

Event	1 (start)	2 (push-up)	3 (push-up+)	4 (end)
Internal rotation (± standard deviation)	16.87° (15.46°)	36.73° (8.35°)	42.75° (8.46°)	18.53° (16.10°)
Upward rotation* (± standard deviation)	19.59° (6.75°)	14.44° (7.6°)	13.93° (6.85°)	19.31° (5.71°)
Posterior tilting (± standard deviation)	-3.69° (7.31°)	-6.51° (5.64°)	-7.72° (4.58°)	-4.13° (7.48°)

* Upward rotation values multiplied by negative 1 for ease of interpretation.

scapular stabilizer, which holds the medial border and inferior angle of the scapula against the thorax during arm elevation.[3] The serratus anterior also acts to contribute to ''normal'' movements of the scapula during arm elevation.[7,10] Normal scapular kinematics are believed to increase the volume of the subacromial space during arm elevation and allow for clearance of the humeral head and rotator cuff tendons.

Our data demonstrated a much smaller degree of scapular upward rotation and less posterior tilt than previous studies[16,18,19,22] at similar humerothoracic elevation angles (Table II). Also, relative downward rotation occurred with increased humeral elevation during the wall push-up. The amount of decreased scapular upward rotation and anterior tilt at the end of the plus portion (event 3) of the push-up exercise (10° or more difference in upward rotation compared to previous studies; Table II), warrants attention because it may lead to a significant decrease in the volume of the subacromial space by bringing the anterolateral acromion into closer proximity to the supraspinatus tendon insertion.[13,16] As a result, the wall push-up plus exercise could lead to irritation of the subacromial space contents leading to injury, rather than reducing such irritation as intended. It should be noted, however, that differences in coordinate systems between studies magnifies differences observed, and that the effect of scapular orientation changes on the subacromial space has been questioned in a recent study.[11]

The differences in scapular upward rotation for the push-up plus as compared to previous studies[16,18,19,22] alternatively may be attributed to the differing nature of weight-bearing on the upper extremity as the comparative literature examined open kinematic chain motions. In contrast, we described the shoulder kinematics of the weight-bearing push-up plus exercise, which has been classified as a closed kinematic chain exercise, where the distal segment was fixed. In theory, open and closed kinematic chain exercises result in differing muscle actions.

Nawoczenski et al[26] reported shoulder kinematics during 2 closed kinematic chain tasks, weight-relief raise and

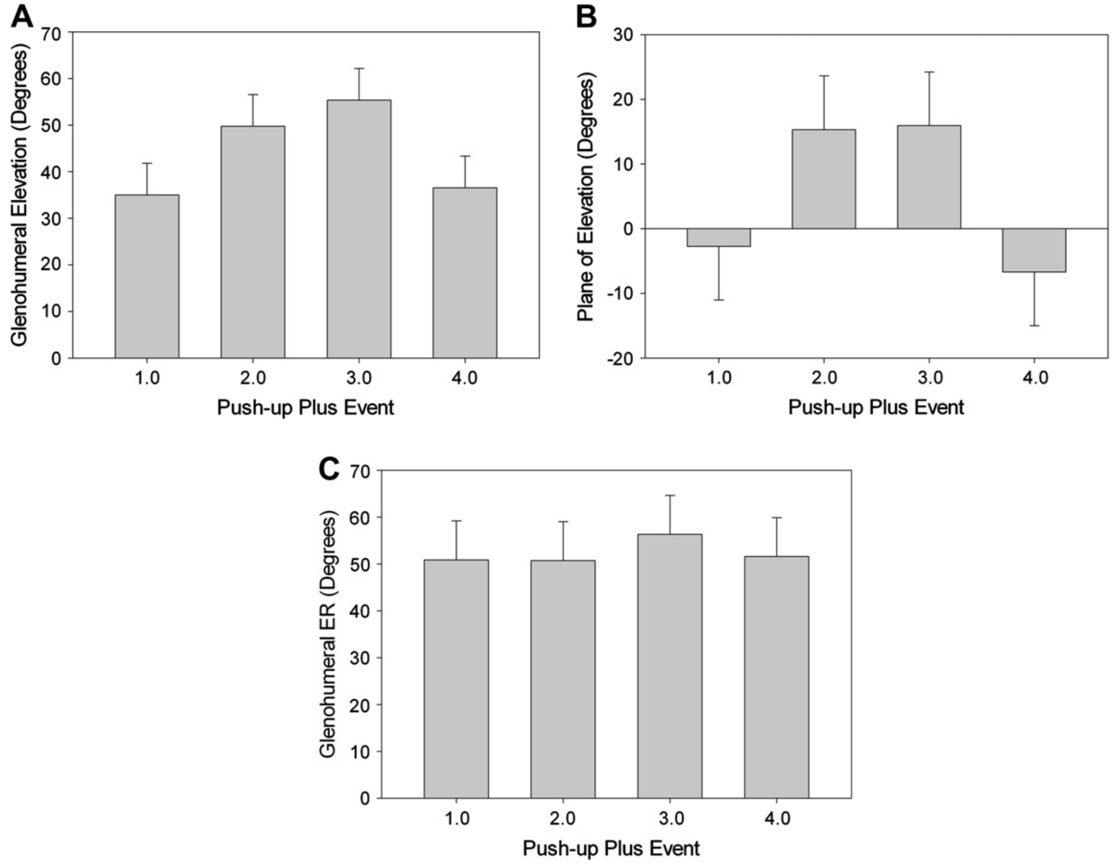

Figure 4 Glenohumeral rotations during the wall push-up plus. **A**, Glenohumeral elevation angle; **B**, glenohumeral plane of elevation (positive values are anterior to the scapular plane and negative values are posterior to the scapular plane; **C**, glenohumeral internal/external (ER) rotation. For elevation angle and external rotation raw data were multiplied by -1 for ease of clinical interpretation. Error Bars denote standard error of the mean. Event 1 = start; event 2 = push-up; event 3 = push-up plus; event 4 = end. Significantly greater glenohumeral elevation and anterior plane of elevation was present for events 2 and 3.

transfer in a wheelchair, in healthy subjects without spinal cord injury. Although the humeral elevation angles for the tasks in Nawoczenski's study were less than in the current study, the position of the scapula was similar with regard to upward rotation in both the weight-relief raise and transfer task, as compared to events 2 and 3 of the push-up plus exercise once differing axis systems are accounted for.

Based on the scapular kinematics of the wall push-up plus exercise reported in this study, caution may be warranted in selecting the wall push-up plus early on during shoulder rehabilitation for patients with subacromial impingement. Alternatively, modifying the exercise by having the patient attempt to actively upwardly rotate the scapula while performing the exercise may improve scapular position and reduce this potential irritation of the rotator cuff tendons. The decreased upward rotation noted in the elevated arm position may be related to the more passive humeral elevation associated with arm placement against the wall.[6] When passively elevating the arm, less scapular upward rotation occurs,[6] and so this may be a mechanism by which the reduced scapular upward rotation occurs. Additionally, the scapular protraction that is occurring through clavicular protraction during the plus phase of the push-up plus exercise may be disadvantageous to the subacromial space.[30] Historically, exercise selection has been based predominately on investigations of muscle activation. Although muscle activation is important information, shoulder kinematic data is also necessary before recommending a particular exercise with regard to protecting the rotator cuff tendons from impingement risk.

To date, shoulder kinematic data during common shoulder rehabilitation exercises are not available in the literature. Therefore, it is difficult to recommend an alternative to the push-up plus for serratus anterior strengthening. However, other exercises that have been shown to demonstrate high serratus anterior activity include the wall slide,[9] dynamic hug,[5] and serratus punch.[5] The dynamic hug and serratus punch exercises are performed in approximately the same plane of motion as the wall push-up plus, and they visually incorporate similar shoulder protraction motions. However, they are open chain exercises which might result in differing kinematics. The wall slide is a closed chain exercise but without emphasis on shoulder protraction, and is performed at a higher angle of

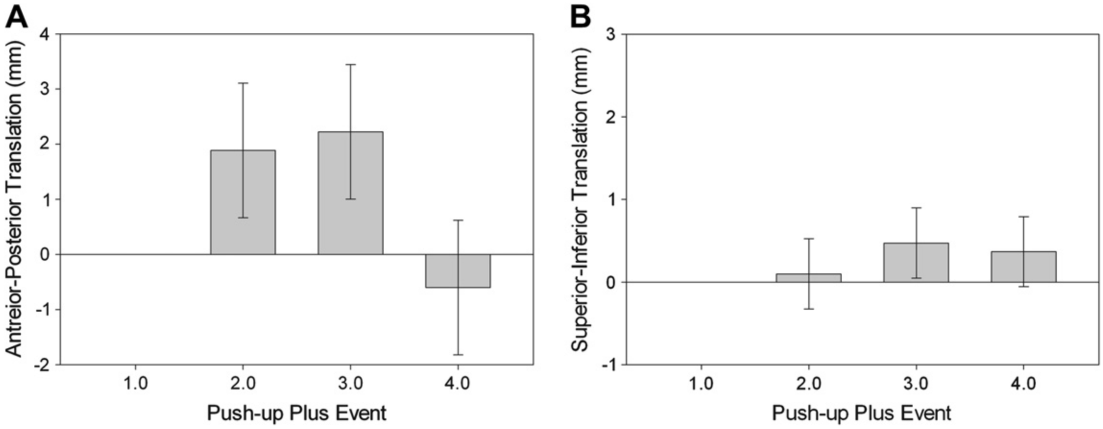

Figure 5 Glenohumeral translations relative to the scapula during the wall push-up plus. **A**, Glenohumeral anterior/posterior translations; **B**, glenohumeral superior/inferior translations. Error Bars denote standard error of the mean. Event 1 = start; event 2 = push-up; event 3 = push-up plus; event 4 = end. Scapular reference point (0 coordinate) is the starting position. Positive values indicate anterior translation.

Table II Comparison of studies reporting average scapular kinematics at various angles of humerothoracic elevation

Study	Humerothoracic elevation angle	Scapular internal rotation	Scapular upward rotation	Scapular posterior tilting
Current Study	66° (Event 1)	17°	20°	-4°
	77° (Event 3)	43°	14°	-8°
Ludewig et al[18]	70° SAb	39°	27°	-6°
	80° SAb	39°	30°	-4°
Ludewig et al[16]	60° SAb	–	23°	-9°
	90° SAb	–	33°	-9°
McClure et al[22]	70° SAb	35°	30°	9°
	80° SAb	34°	32°	10°
	70° flexion	42°	32°	9°
	80° flexion	42°	38°	10°
Lukasiewicz et al[19]	90° SAb	41°	27°	22°

SAb, scapular plane abduction.

elevation and thus, theoretically, could have increased scapular upward rotation relative to the wall push-up plus. Kibler et al[12] demonstrated moderate serratus activation in several exercises emphasizing scapular retraction, including a low row. Choosing one of these other exercises on the basis of presumed kinematics would be purely speculative. Thus they can only be recommended as alternatives to the wall push-up plus, due to their level of serratus anterior activation. Further research is needed to examine shoulder kinematics during shoulder rehabilitation exercises and enable more scientific assignment of appropriate exercises for specific shoulder pathologies. An optimal serratus anterior exercise would incorporate both high serratus activation and scapular kinematics consistent with normal function and minimizing external or internal impingement risk.

There are some limitations of the current study. Our subjects represent a relatively young and healthy population with no history of shoulder pathology. As a result, one should be cautious when generalizing the results of this study to patients with shoulder pain and older populations. The use of healthy young subjects in this study was necessary to investigate kinematics in ‘‘normal’’ individuals to determine a baseline for kinematics in the wall push-up plus exercise. The influence of the bone pins on kinematics due to skin tension and/or pain is another potential limitation of this study. In order to minimize the effect of skin tension on shoulder kinematics, the skin was released around the pins at the time of insertion. The influence of pain on kinematics of the tested shoulder likely was minimal, as subjects reported a mean pain rating of 1.1/10 on a numeric scale during the exercise. Finally, translations of the humeral head center are common descriptors of glenohumeral joint kinematics. However, these descriptors do not account for differences in humeral retroversion angle that may be present across subjects, nor do they describe the kinematics that are occurring directly at the articular joint surfaces.

Conclusion

The push-up plus exercise is often modified to be performed against a wall in order to decrease the amount of weight-bearing through the glenohumeral joint and to avoid compression and further irritation of the rotator cuff muscles. The findings of this study of decreased upward rotation and increased internal rotation during the wall push-up plus exercise indicate that this exercise may put the glenohumeral joint in a position that decreases the available subacromial space and creates risk for impingement.[16] Taking these findings into account, clinicians may want to reconsider implementing the wall push-up plus exercise or modify the exercise to increase scapular upward rotation early on in the rehabilitation of subacromial impingement. This is especially true if the exercise causes discomfort because it may further exacerbate symptoms and delay the healing process.

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