Application of statistical parametric mapping for comparison of scapular kinematics and EMG

Type of Article: short communication

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Keywords: Statistical parametric mapping; shoulder; scapular kinematics; EMG; load

ABSTRACT (249words)

Scapular kinematics and EMG are frequently measured as a functional assessment of the shoulder. Previous studies have compared interval averaging for these time series data, but it is not clear whether this method exactly captures the dynamics of scapular kinematics and muscle activity. Statistical parametric mapping (SPM) can be used to compare time series data. The purpose of this study was to investigate whether there is a difference between the results of SPM and interval averaging (every 10° or 30°) in comparing scapular kinematics, EMG, and EMG ratio. Scapular kinematics and EMG of the upper trapezius (UT), middle trapezius (MT), and lower trapezius (LT) and serratus anterior (SA) were measured in 21 healthy males. Tasks included arm raising and lowering with or without load, and we compared scapular kinematics, EMG, and EMG ratio in the loaded and unloaded conditions. Results suggest disagreement between SPM and interval averaging. Characteristic results are that for scapular kinematics during lowering SPM showed a decrease in upward rotation in only the regions 113-65° and 42-30°, while interval averaging showed a decrease in all range. For EMG during lowering, SPM results were not significantly different in SA over 50-48 and 45-30°, while interval averaging suggested increased activity in all ranges. For EMG ratio during raising, SPM showed no significant difference, while interval averaging showed a decrease in UT/LT during the latter period. These results indicate that SPM provides better resolution regarding effect regions than interval averaging, and suggest that SPM may improve shoulder function assessment accuracy.

1 Introduction

The evaluation of scapular kinematics and electromyography (EMG) of scapulothoracic muscles can indicate pathological state and can also be useful in subsequent appropriate treatment. When comparing scapular kinematics almost all previous studies have compared measurements using interval averaging (e.g., humeral elevation 31-60, 61-90, and 91-120°) as a representative value (Ludewig and Cook, 2000; Michener et al., 2016). However, since scapular kinematics and EMG change continuously in time, interval averaging may provide inadequate temporal resolution (Zdravkovic et al., 2020). Statistical parametric mapping (SPM) has been attracting attention recently, because does not require *a priori* time series reduction, and can be used to control both Type I and Type II errors at the entire time series level (Pataky et al., 2013; Robinson et al., 2021). In this study, we compared scapular kinematics and EMG under loaded and unloaded conditions using SPM and interval averaging. A loaded condition was included because even low-to-moderate loads are known to produce substantial changes in shoulder dynamics (Antony and Keir, 2010; Reed et al., 2016).

The purpose of this study was to elucidate differences between the results of SPM and interval averaging in scapular kinematics and EMG ratio during arm raising and lowering with or without load.

2 Materials and methods

2.1 Participants

Twenty-one healthy males (age, 24.3 ± 3.5 years; height, 171.1 ± 4.9 cm; mass, 62.6 ± 10.2 kg) volunteered for this study. We chose this sample size based on pilot studies which showed that SPM was sufficiently sensitive to identify differences in samples of this size (Aliaj et al., 2021, 2022; Gaudet et al., 2018a; Ribeiro et al., 2017). We did not conduct formal power analysis because the primary goal was to compare different analysis methods, and it is generally not possible to calculate a single sample size that yields equivalent power across all methods. Exclusion criteria included: upper limb orthopedic or nervous system abnormalities. Written informed consents were obtained from participants prior to the experiment. All study procedures were approved by the Ethics Committee of Kyoto University Graduate School of Medicine (approval number: R1347-2).

2.2 Experimental procedures

In the standing position, participants performed sagittal plane upper limb raising and lowering along a bar under loaded (3 kg) and unloaded conditions (Fig.1). The non-dominant limb was measured because the dominant hand is often used in daily life, and individual characteristics are greatly expressed in scapula kinematics and EMG, then natural change with load may not occur. The preferred throwing limb was defined as the 'dominant' limb. The participants elevated then lowered their upper limb, each over 4 s, following a metronome at 60 beats/min for three consecutive cycles (24 s). Participants practiced with and without load before measurements were made.

2.3 Measurement of scapular kinematics

The measurement of scapular kinematics followed (Umehara et al., 2018). We measured scapula and humerus motion using a 6-degrees-of-freedom electromagnetic tracker (Liberty, Polhemus, Colchester, VT, USA) at 120 Hz. The device consists of a transmitter, receiver, and digitizing stylus. Each sensor was attached to the scapular acromion, the midpoint of the humerus (attached over a thermoplastic cuff wrapped), and the sternum using adhesive tape. The bony landmarks of the scapula, humerus, and sternum were palpated and digitized using the stylus to form segments and local coordinate systems. Coordinate system definitions followed International Society of Biomechanics recommendations (Wu et al., 2005).

2.4 Measurement of EMG

We measured muscle activity using surface EMG (TeleMyo 2400; Noraxon, Scottsdale, AZ, USA) at 1500 Hz. The in-phase signal removal ratio, impedance and gain were >100 dB, >100 dMohm and 500 dB, respectively. Sub-electrode skin was shaved and cleaned using scrub gel and alcohol. Disposable pregelled Ag-AgCl electrodes (Blue Sensor; Medicotest, Olstykke, Denmark) were applied to the upper trapezius muscle (UT), middle trapezius muscle (MT), lower trapezius muscle (LT), and serratus anterior muscle (SA). The inter-electrode distance was 20 mm. Electrode locations followed the previous study (Umehara et al., 2021). Based on a previous study (Yamauchi et al., 2015), we measured the EMG of each muscle during maximal voluntary contraction for amplitude normalization purposes. EMG was normalized by the EMG during maximal voluntary contraction and presented as a percent (%MVC). The EMG during maximal voluntary contraction was measured once for three seconds in each muscle after practicing several times and making sure they could exert all their strength.

2.5 Data processing

During each raising and lowering phase, scapular angles relative to the thorax were calculated for every 1° of humeral elevation from 30 to 120°, and the averages across three measurements were used for statistical analysis. We analyzed scapular kinematics in humeral elevation only up to 120°, because previous studies (Karduna et al., 2001) have shown that measurement error increases beyond 120°. The scapular angle at the nearest neighbor value of the measured humeral elevation angle was used for integer values from 30 to 120°. We processed the raw EMG signals using zero-phase-lag filter. In addition, raw EMG signals were processed using a band-pass filter (10-450 Hz; 4-order; Butterworth) and low-pass 5-Hz filter to remove noise (Gaudet et al., 2018c, 2018b). Mean values over three seconds were used as representative values. EMG and kinematic data were synchronized using the spike trigger at the beginning of the measurement. The EMG data were calculated every 1° at the humeral elevation angle from 30 to 120° in each raising and lowering phase EMG means over about 22 ms were used for each 1°.

2.6 Statistical analysis

SPM1d version 0.4 (http://www.spm1d.org) (Pataky et al., 2013) was used for the statistical analysis of scapular kinematics, EMG, and EMG ratio. Two-tailed paired SPM t-tests were used to test for load effects on scapular kinematics. Similarly, EMG of UT, MT, LT, and SA and EMG ratios of UT/MT, UT/LT, and UT/SA were compared between load and unload. We also conducted interval averaging analysis and qualitatively compared to the SPM results. Mean humeral elevation angles were calculated over both 10° (Kai et al., 2016; Kon et al., 2008) and 30° intervals (Camci et al., 2013; De Castro et al., 2014; Michener et al., 2016). A Type I error rate of 0.05 was used in all tests. All analyses were performed using Matlab R2020a (Mathworks, Natick, MA, USA).

3 Results

3.1 Scapular kinematics

During raising, external rotation significantly increased, and posterior tilt significantly decreased when loaded. During lowering, upward rotation and posterior tilt significantly decreased when loaded. SPM and interval averaging results differed for posterior tilt (raising) and upward rotation (lowering) (Table1, Fig.2A-C).

3.2 EMG

EMG of all muscles significantly increased when loaded. SPM and interval averaging results differed for SA (lowering) (Table1, Fig.3A-C).

3.3 EMG ratio

UT/MT and UT/LT significantly decreased when loaded. SPM and interval averaging results differed for both ratios in both movement phases (Table1, Fig.4A-C).

4 Discussion

This study investigated the effects of load on scapular kinematics and EMG during arm raising and lowering, separately using SPM and interval averaging. We then focused on identifying differences between the results of SPM and interval averaging. Results suggest disagreement between SPM and interval averaging for several scapular kinematics and EMG variables. This supports previous findings that interval averaging and other ad hoc time series reduction techniques can distort or bias the underlying data (Pataky et al., 2013).

For scapular kinematics in the lowering phase, SPM showed a load-induced decrease in upward rotation in the regions 113-65 and 42-30°, but interval averaging showed a decrease over the entire range (Fig.2). In addition, the two different interval resolutions (10° and 30°) gave different results in external rotation and posterior tilt during raising (Fig.2B, C). Interval averaging may therefore represent under-sampling. Supplementary results considering other common metrics (root mean squared error and correlations) reinforced the observation that inadequate resolution can distort the results (see Supplementary Material). These results suggest that resolution discrepancies amongst previous studies could have caused the reported inconsistencies.

SPM showed no significant load effect for SA EMG at 50-48 and 45-30° (lowering). This contradicts interval averaging's result which suggests significant increases over the entire range. SPM similarly exhibited conflicting results for both UT/LT and UT/MT EMG ratios during raising. For variables like EMG ratio, which can change greatly with each 1° of humeral elevation. Highly erratic variables like this may require increased resolution in order to capture high-frequency content. Neither SPM nor interval testing should be used if the effective resolution is insufficient to capture those changes.

Choosing analysis methods for scapular kinematics and EMG of scapulothoracic muscles should follow the aim and data type. Each method has pros and cons. For example, the SPM avoids summary metric extraction (Pataky et al., 2016a), but cannot assure single point/feature comparison and cannot avoid the normalization (i.e., time or angle) (Pataky et al., 2022). In contrast, scalar analysis (e.g., interval averaging or peak values) allows us to compare single-point values such as peak, minimum, and median (Degrave et al., 2020) but cannot avoid continuum summary metric extraction (Pataky et al., 2016a). Furthermore, scalar analysis may increase the false positive rate when continuous one-dimensional data is converted to zero-dimensional data (Pataky et al., 2016b). This study also showed why different interval resolutions may be non-ideal. Given the pros and cons of each method and our findings, it may be desirable to select analyses based on the purpose of the study or run multiple analyses using multiple methods. When selecting the analysis, we would recommend using SPM if we want to compare continuous data and scalar analysis if we want to compare features (e.g., interval averaging or peak values). When combining analyses, insofar as the methods agree one can be reasonably confident in the detected effect(s). If they disagree, then that disagreement ought to be explained. We believe this will enable us to assess shoulder joint function more accurately and we can utilize it in clinical settings.

In conclusion, we investigated the effects of load on scapular kinematics and EMG during slow, cyclical upper limb raising and lowering using SPM and interval averaging. SPM and interval averaging gave different results, due predominantly to insufficient resolution and/or false positive rate in the latter. Using SPM in the comparison of shoulder dynamics may avoid resolution-borne errors of conventional interval averaging methods, and may therefore yield greater inter-study consistency and ultimately more accurate assessments of shoulder function.

5 Authors' Contributions

All authors conceived and designed the research. KK and JU performed the experiment and analyzed the data. All authors interpreted the results. KK, JU, TP, MY, TH, and YU wrote the manuscript. JU, TP, MY, TH, YU, and NI edited and revised the manuscript. All authors have approved the final version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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	Results of load compared with unload	humeral elevation angles with significances			Results of load compared with unload	humeral elevation angles with significances		
	Raising phase	SPM	10°	30°	Lowering phase	SPM	10°	30°
Scapular kinematics								
In/Ex Rot.	Increase in Ex	76-120°	70-79,80-89,90-99, 100-109,110-120°	60-89,90-120°				
Down/Up Rot.					Decrease in Up	113-65,42-30°	all range	all range
Pos/Ant Tilt	Decrease in Pos	89-120°	30-39,80-89,90-99, 100-109,110-120°	30-59,90-120°	Decrease in Pos	all range	all range	all range
EMG								
UT	Increase in UT	all range (except 120°)	all range	all range	Increase in UT	all range (except 46°)	all range	all range
MT	Increase in MT	all range	all range	all range	Increase in MT	all range	all range	all range
LT	Increase in LT	all range (except 120°)	all range	all range	Increase in LT	all range	all range	all range
SA	Increase in SA	all range	all range	all range	Increase in SA	all range (except 50-48,45-30°)	all range	all range
EMG ratio								
UT/MT	Decrease in UT/MT	36-39,44-84,86-90, 94-98,105-110,112°	all range	all range	Decrease in UT/MT	88,60-53,48-40°	109-100,99-90,89-80,79-70, 69-60,59-50,49-40,39-30°	all range
UT/LT	Decrease in UT/LT		70-79,80-89, 90-99,100-109°	60-89,90-120°	Decrease in UT/LT	73-65,60-53, 50-49,47-43°	all range	all range
UT/SA								

Table1 Comparison of SPM and interval averaging results.

SPM: Statistical Parametric Mapping, 10°: interval averaging every10°, 30°: interval averaging every 30°, In Rot.: internal rotation, Ex Rot.: external rotation, Down Rot.: downward rotation, Up Rot.: upward rotation, Pos Tilt: posterior tilt, Ant Tilt: anterior tilt, UT: upper trapezius muscle, MT: middle trapezius muscle, LT: lower trapezius muscle, SA: serratus anterior muscle

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Figure1 Measurements of scapular kinematics and EMG.

Figure2 Scapular kinematics in load and unload.

Unload is indicated by a blue line, load by a red line. Panel A shows the results of SPM, panel B shows the results of interval averaging every 10°, and panel C shows the results of interval averaging every 30°. The gray area in panel A and * in panel B and panel C indicate that there was a significant difference between load and unload. The scapula angle was defined as internal rotation (+) and external rotation (-), upward rotation (-) and downward rotation (+), and posterior tilt (+) and anterior tilt (-). The humeral angle was defined as elevation (+) and supination (-). In Rot.: internal rotation, Ex Rot.: external rotation, Down Rot.: downward rotation, Up Rot.: upward rotation, Pos Tilt: posterior tilt, Ant Tilt: anterior tilt

Figure3 EMG in load and unload.

Unload is indicated by a blue line, load by a red line. Panel A shows the results of SPM, panel B shows the results of interval averaging every 10°, and panel C shows the results of interval averaging every 30°. The gray area in panel A and * in panel B and panel C indicate that there was a significant difference between unload and load. UT: upper trapezius muscle, MT: middle trapezius muscle, LT: lower trapezius muscle, SA: serratus anterior muscle

Figure4 EMG ratio in load and unload.

Unload is indicated by a blue line, load by a red line. Panel A shows the results of SPM, panel B shows the results of interval averaging every 10°, and panel C shows the results of interval averaging every 30°. The gray area in panel A and * in panel B and panel C indicate that there was a significant difference between load and unload. UT: upper trapezius muscle, MT: middle trapezius muscle, LT: lower trapezius muscle, SA: serratus anterior muscle

Figure1 Measurements of scapular kinematics and EMG.

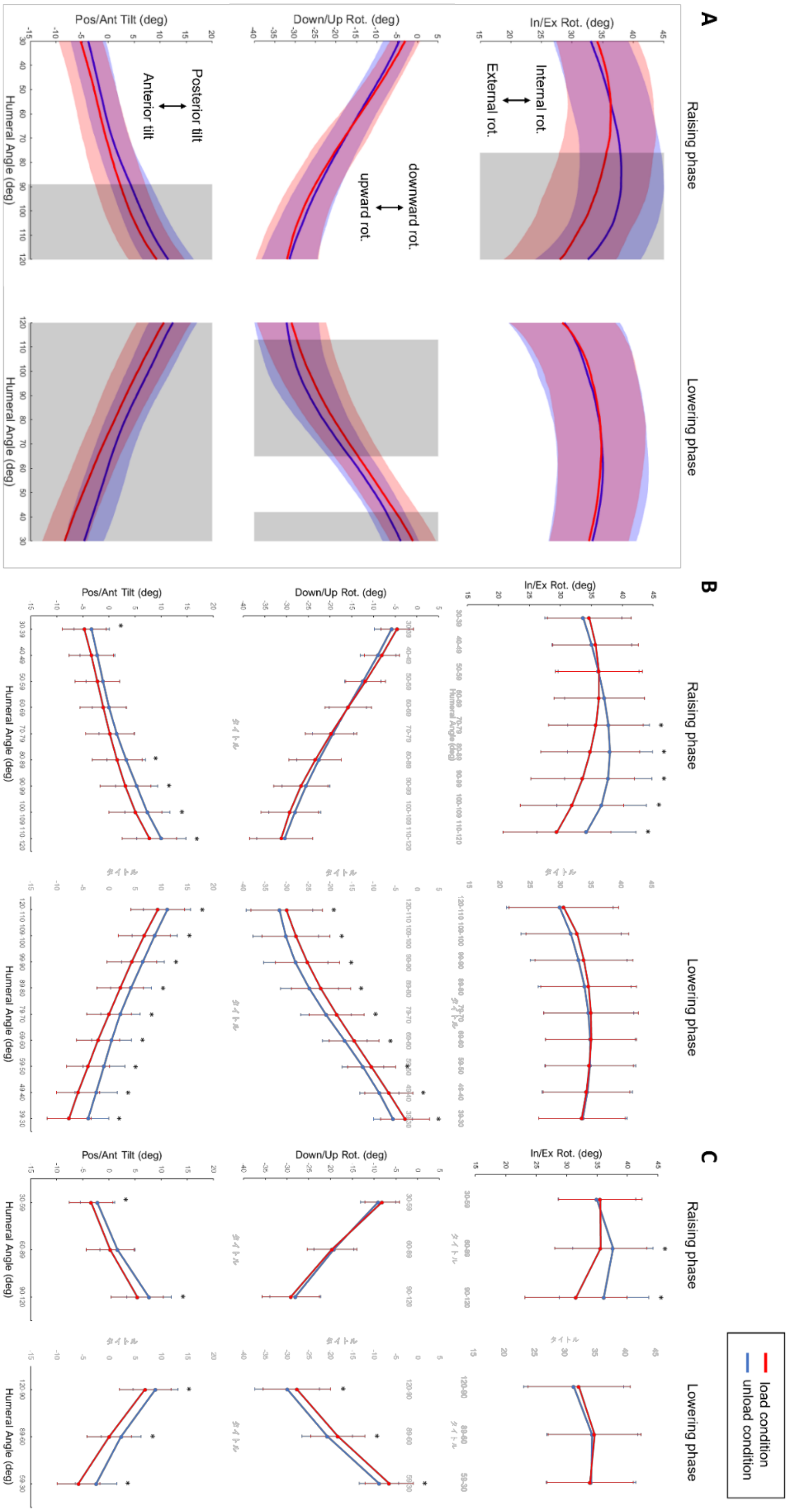


Figure2 Scapular kinematics in load and unload.

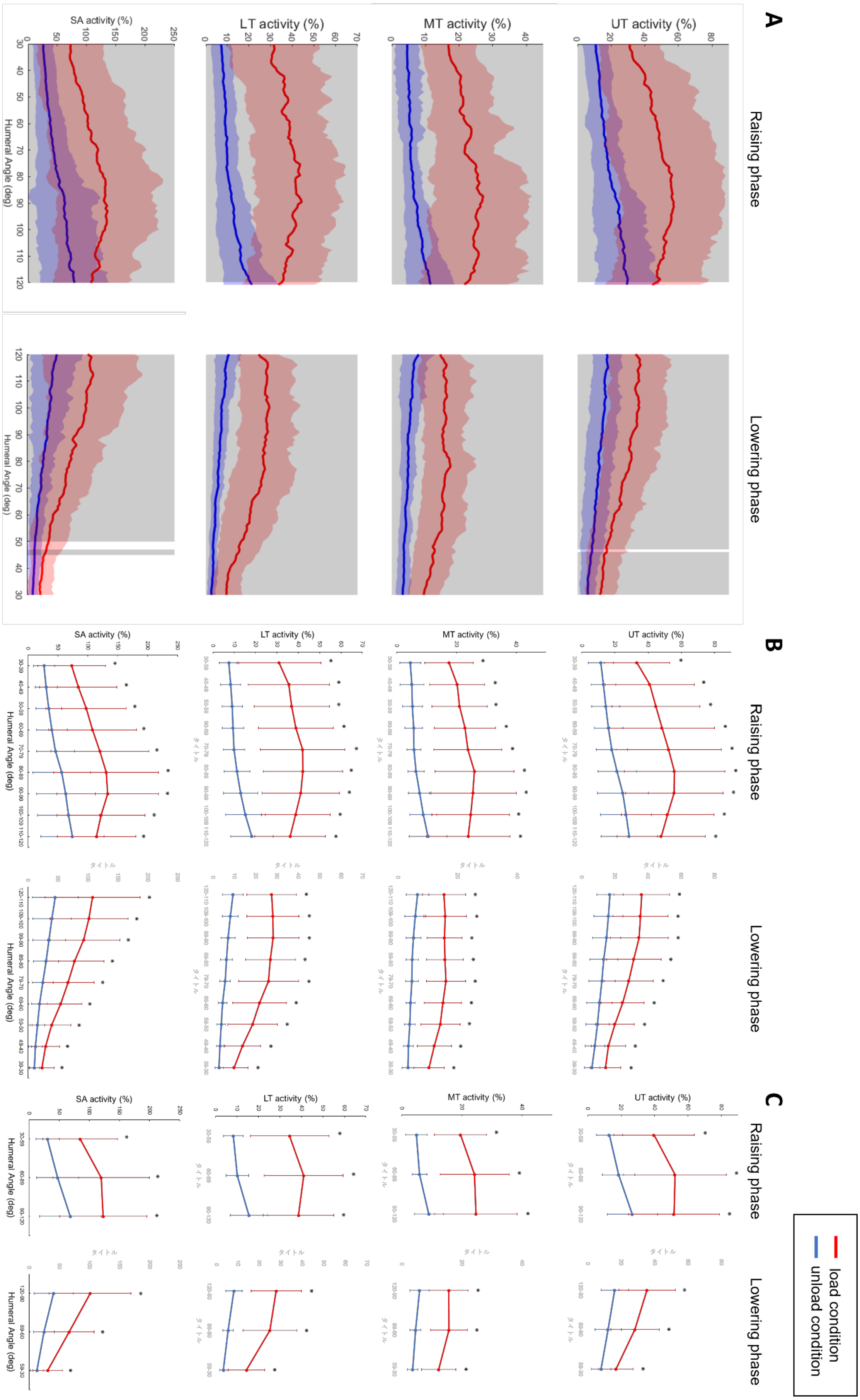


Figure3 EMG in load and unload.

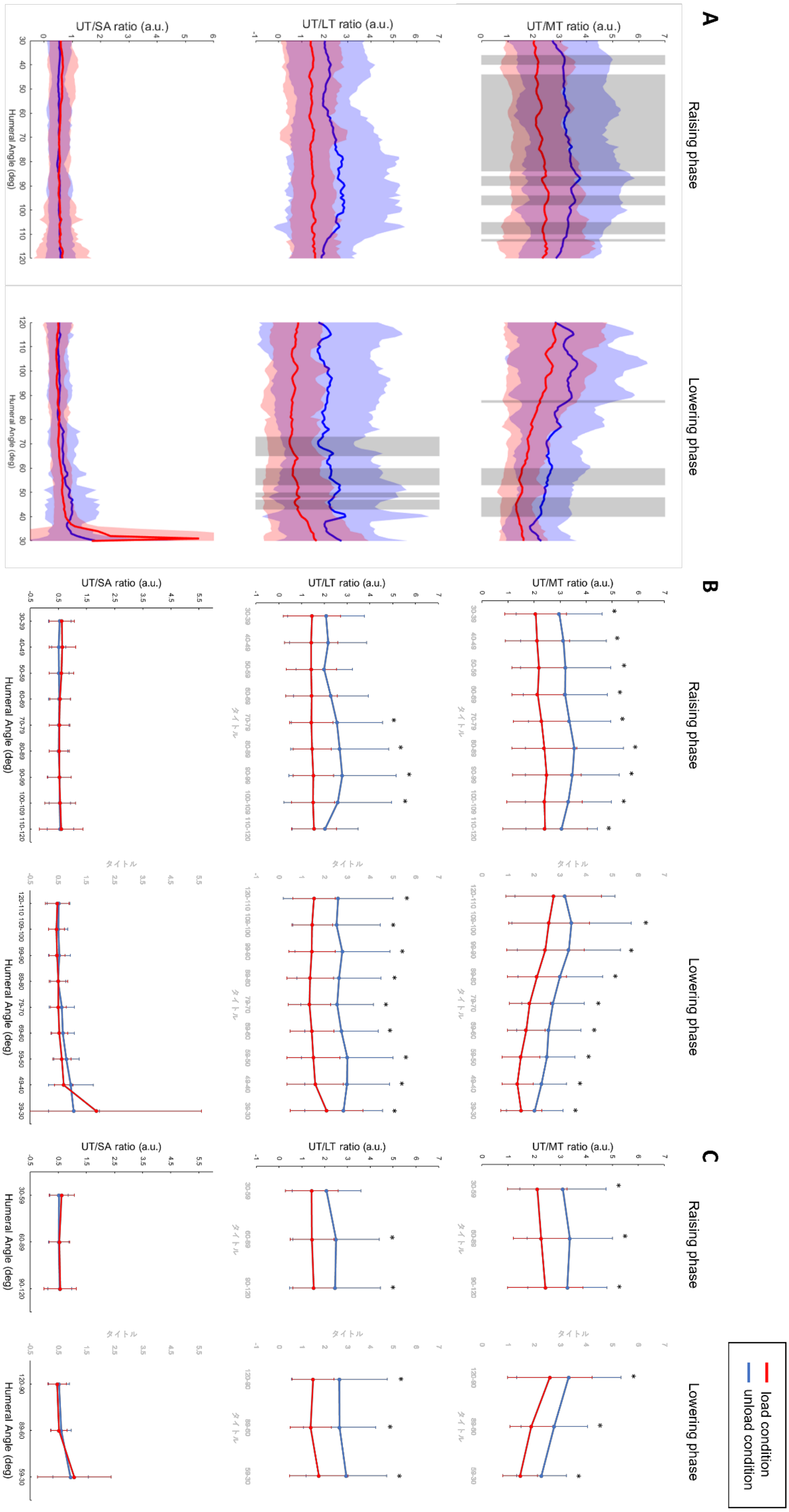


Figure4 EMG ratio in load and unload.

Supplementary Material

Previous studies have compared scapular kinematics using RMSE (Root Mean Squared Error) and correlations as well as interval averaging. In this supplementary material, we show the results of RMSE and correlations of scapula kinematics and discuss them in the context of the main manuscript's SPM results.

1. RMSE

We considered two mean trajectories yA(q) and yB(q), where q indicates humeral elevation angle, and where there is a total of Q angle points. yA and yB indicate the loaded and unloaded conditions, respectively. We calculated RMSE as follows:

$$\text{RMSE} = \sqrt{\frac{1}{Q}\sum_{q=1}^{Q}(\overline{yA}(q) - \overline{yB}(q))^2}$$

where q indexes angle points.

Table S1 shows the results of RMSE. The results of RMSE and SPM differed. While RMSE produced a single value throughout the phase, the SPM can examine whether there is a difference between conditions at each humeral elevation angle.

We can compare the same units as the original data using RMSE and it is easy to calculate. However, RMSE has no time resolution. In addition, we should consider the results of RMSE showed effects (i.e., differences with respect to variability) and not just the differences between load and unload conditions.

Table S1. RMSE of scapular kinematics

	Ascending phase	Descending phase
	Mean	Mean
Scapula kinematics		
In/Ex Rot.	3.00	0.58
Down/Up Rot.	0.89	2.35
Pos/Ant Tilt	1.69	2.63

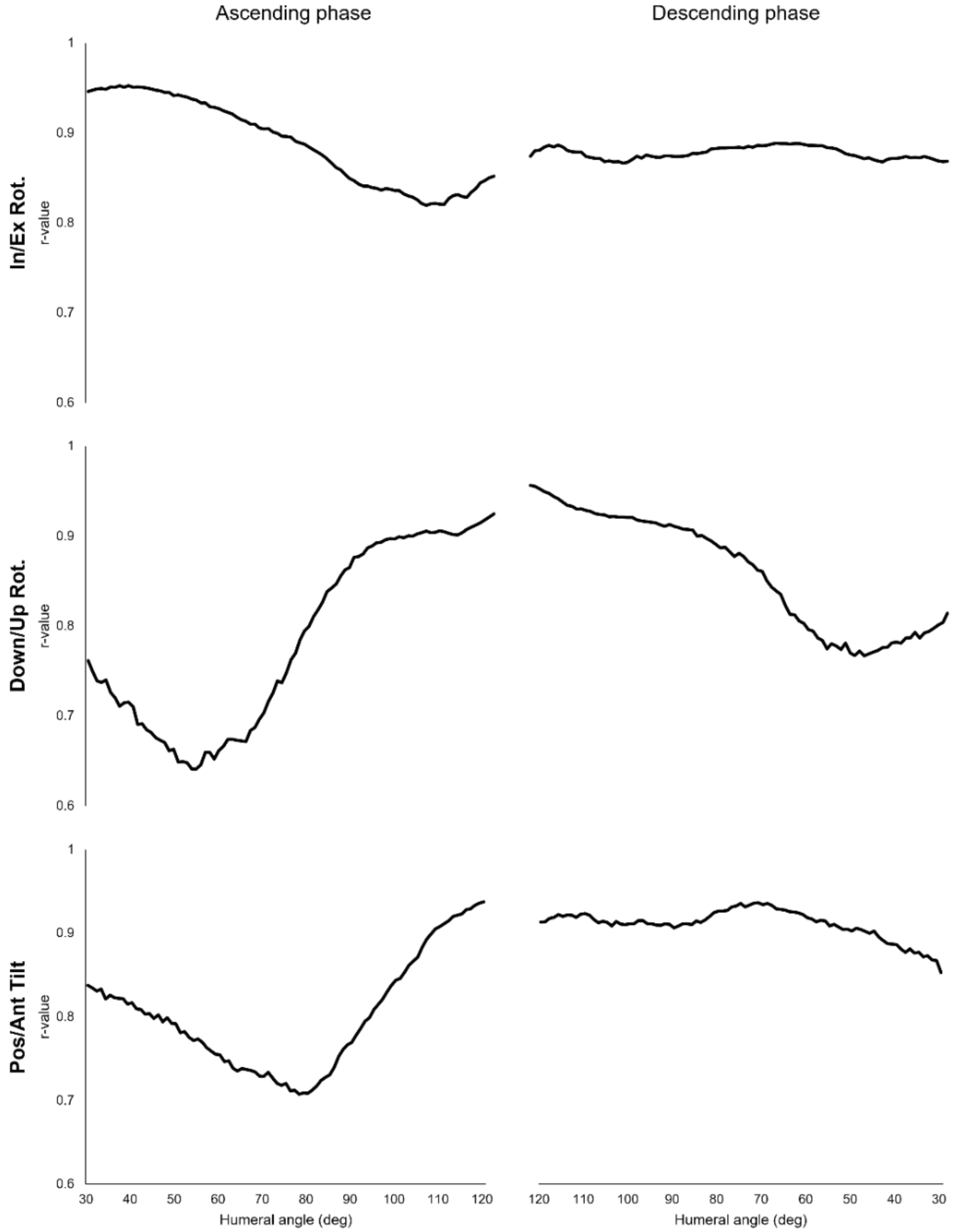
In Rot.: internal rotation, Ex Rot.: external rotation, Down Rot.: downward rotation, Up Rot.: upward rotation, Pos Tilt: posterior tilt, Ant Tilt: anterior tilt

2. Correlations

For each humeral elevation angle, we calculated Pearson coefficients (r-values) to quantify the linear correlation strength between loaded and unloaded conditions. Figure S1 shows the resulting r-values as trajectories, and --- as an illustration of the meaning of these r-values --- Figure S2 shows a scatterplot of loaded vs. unloaded conditions in downward/upward rotational angles at the instant of maximum absolute r-value (humeral elevation angle = 120° for the descending phase).

Correlation analysis allows us to investigate whether the loaded and unloaded conditions are related at each humeral elevation angle like SPM. While a critical r-value could be calculated, with SPM results presented like those in the main manuscript, r-values are not typically used in the SPM literature for two reasons. First, while t-values range an unbound (i.e., ranging from $-\infty$ to $+\infty$), r-values are bounded to the range [-1, +1], so it is generally difficult to perceive r-value changes when correlations are strong. Second, typical r-value interpretations (e.g. $r = 0.6$ implies “moderately strong” correlation) do not hold for trajectory-level results because large r-values are expected to randomly occur with greater probability for trajectory data.

Figure S1. Scapular kinematics r-value trajectories for both ascending and descending movement phases.



The horizontal axis of each graph shows the humeral elevation angle, and the vertical axis shows the r-value (correlation between loaded and unloaded conditions) at each humeral elevation angle. The upper part shows the results of the internal/external rotation, the middle part shows the upward/downward rotation, and the lower part shows posterior/anterior tilt. The left side shows the raising phase and the right side showing the lowering phase. In Rot.: internal rotation, Ex Rot.: external rotation, Down Rot.: downward rotation, Up Rot.: upward rotation, Pos Tilt: posterior tilt, Ant Tilt: anterior tilt

Figure S2. scatterplot of loaded vs. unloaded at the instant of maximum absolute r-value