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Inter-joint coordination of shoulder joint complex during two different arm elevation speeds

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1. Introduction

The shoulder joint comprises the glenohumeral (GH), scapulothoracic (ST), acromioclavicular, and sternoclavicular joints. Although various daily activities and sports movements consist of coordinated movements of these joints, the GH and ST joint movements have been mainly analyzed because the ranges of motion of these joints are significantly larger than those of the other joints. The scapula plays a role in maintaining the proper joint configuration of the GH joint and is the base for the origin of shoulder muscles, such as the rotator cuff and the deltoid (Inman et al., 1944; McClure et al., 2009; Seitz et al., 2012). Therefore, understanding the features of the GH and ST joint movements during shoulder motion is critical for shoulder injury prevention and rehabilitation (McClure et al., 2009; Seitz et al., 2012).

Scapulohumeral rhythm (SHR) is the kinematic feature of the coordinated movement between GH and ST joints during arm elevation and is also used as an indicator for evaluating shoulder function. SHR is represented as the GH and ST joint increment angles ratio, initially reported in 1944 (Inman et al., 1944), and has since been used as the primary outcome of coordinated movement of the GH and ST joints in numerous studies (Forte et al., 2009; Kon et al., 2008; Madokoro et al., 2016; Matsuki et al., 2011; Walker et al., 2015). However, a limitation of the SHR is that it does not include velocity-related variables. Moreover, the dynamic coordination of the GH and ST joints has been frequently assessed using visual observation such as the scapular dyskinesis test (McClure et al., 2009; Tate et al., 2009). Although visual observation-based assessments have moderate reliability (Huang et al., 2015; Kibler et al., 2002; McClure et al., 2009), the quantitative evaluation of the dynamic coordinated movement of the shoulder joint may also be necessary.

A few studies have concluded that the SHR is affected by the arm elevation speed (Prinold et al., 2013; Sugamoto et al., 2002), although they did not focus on the 0–30° of elevation. Inman et al. stated that the scapula seeks its exact position to the humeral head in the first 30° or 60° and that the GH joint settles at the stabilized position (Inman et al., 1944). They called the first phase the "setting phase." The humeral head may be translated upwards unless the GH and ST joints work coordinatedly in the setting phase (Longworth et al., 2018). Based on clinical experience, patients with shoulder injuries often report pain during sudden, fast arm movements from a resting position, such as quickly reaching to pick something up. Thus, understanding how arm elevation speed affects the dynamic coordination of the GH and ST joints during the setting phase is crucial for assessing shoulder movement and rehabilitating shoulder joint disorders.

Previous studies have examined the motion of the ST joint relative to the GH joint from a resting position (Umehara et al., 2019). These studies concluded that scapular movement varied among participants during 30° of shoulder abduction. However, the analysis relied on discrete variables, calculated by dividing shoulder joint angles into 30-degree intervals, which may have obscured the dynamic coordination between the GH and ST joints. Therefore, analyzing the continuous time series data of the dynamic coordination between the GH and ST joints, particularly during the setting phase, could offer new insights into their contribution patterns during arm elevation.

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Cyclogram facilitates the visualization of the dynamic coordinated movement between two joints. This method is obtained by plotting joint-related variables against other joints simultaneously through the entire movement, and it can represent the inter-joint coordination pattern of complex movement. In the gait analysis, many studies have analyzed some participants, such as individuals with hip or knee osteoarthritis, those with total hip arthroplasty, or those with hemiplegic stroke (H. S. Lee et al., 2021; Longworth et al., 2018; Park et al., 2021). These studies reported that the gait speed affects the inter-joint coordination of hip and knee joints (Chiu and Chou, 2012). Like the gait study, some features in the coordinated movement between the GH and ST joints may be expected from the results of the cyclogram.

Therefore, this study aimed to investigate the effect of arm elevation speed on the inter-joint coordination of the shoulder joint complex during arm elevation by using the cyclogram, particularly focusing on the setting phase. We hypothesized that the coordinated movement between the GH and ST joints during the setting phase would show characteristics depending on the arm elevation speed.

2. Methods

2.1. Participants

This study was conducted in accordance with the Declaration of Helsinki and approved by the ethical review board of our institution (number: 20543). Written informed consent was obtained from all the participants. This study is a cross-sectional study and healthy males aged between 20 and 30 years were directly recruited. Participants with a history of upper-limb surgery, shoulder musculoskeletal injuries (such as rotator cuff tears or impingement syndrome) within a year of the experimental day, pain during the fastest shoulder movement with maximum voluntary contraction, and inability to elevate upper extremities to the maximal elevation were excluded from the study.

2.2. Data collection

Eight 14-mm reflective markers were attached with double-sided tape in the following positions according to International Society of Biomechanics recommendations (Wu et al., 2005): suprasternal notch, xiphoid process, the spinal process of the 7th cervical and 8th thoracic vertebrae, and lateral and medial epicondyles on both sides (Fig. 1). The humeral marker cluster, which comprises three 14-mm markers, was fitted on the midpoint of the humerus. An acromion marker cluster (AMC) comprising three thin bars with 6-mm markers on the distal end was applied to the skin over the posterior side of the flat part of the acromion (Fig. 1). The locations of the reflective markers and the marker clusters were measured using an optical motion capture system (Optitrack, NaturalPoint, Inc., Corvallis, OR) with eight cameras at a sampling rate of 120 Hz. Next, the template of the scapula was created using a handmade scapular locator comprising three adjustable styluses and 6-mm markers by the palpation. A trained physical therapist (T.U.) palpated the position of the acromion angle (AA), trigonum spinae (TS), and inferior angle (IA) of the scapula at the resting position and adjusted the size of the scapular locator for each participant. In the double calibration described below, the scapular locator, which mimics the shape of the scapula, was used to identify the positions of the scapular anatomical landmarks.

The participants were seated on a chair without armrests or a backrest. The scapular anatomical landmark positions relative to the AMC were calibrated. Since the positional relationship between the AMC and scapular anatomical landmarks is not constant due to soft tissue artifacts, previous studies have recommended multiple calibrations for estimating the ST joint angle (Bourne et al., 2009; Brochard et al., 2011). Consequently, a double calibration method was used with two seated positions as follows: a resting position and a 90° abduction with full elbow extension while holding weights equivalent to 2% of body weight.

The scapular locator and a portable ultrasonography device (SONON L, Aison Co., Ltd. Saitama, Japan) were used to quantify the positions of IA, TS, and AA. The bottoms of the styluses of the scapular locator were placed on the IA and TS, which were identified through the palpation of the trained experimenter (T.U.). The markers' positions on the scapular locator were also captured using the motion capture system (Fig. 1). The position of scapular anatomical landmarks in the abduction posture was calculated by coordinate transformation from the scapular locator's local coordinate system into a global coordinate system.

Accurately quantifying the position of the AA is challenging when the shoulder is abducted to a certain degree, particularly for people with muscle or fat thickness. To address this issue, a reliable ultrasonography device was used (Supplementary materials for the reliability test). AA images were captured using the ultrasonography device, which had three 14-mm markers placed on the top and both sides, positioned over

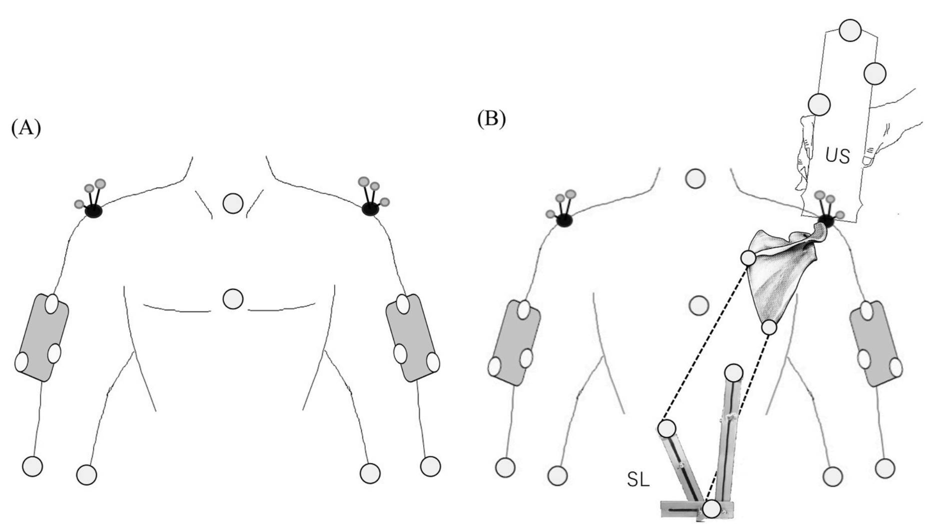

Fig. 1. — (A) Location of the reflective marker positions on the front side. An acromion marker cluster on both shoulders composed of 2.5, 1.5, and 1.0 cm bars and a base with 1.4 cm diameter. (B) Location of the reflective marker positions on the back side, the ultrasonography (US), and a scapular locator (SL). To locate the position of the acromion angle (AA), the experimenter positioned the ultrasonography device over the lateral edge of the acromion. To facilitate the recognition of the scapula and the acromion marker cluster, the location of the US is drawn by shifting. The scapular locator, which was adjusted according to the size of each participant's scapula, was used to identify the two anatomical landmarks as follows: the trigonum spinae and the inferior angle.

the lateral edge of the acromion, by a trained experimenter (T.U.) (Fig. 1). The positions of the markers on the ultrasonography device were recorded simultaneously using the motion capture system. Furthermore, the precise position of the AA under the thickened deltoid muscle could be detected by combining the ultrasonography device's image and the ultrasonography device 's position and orientation in the global coordinate system (Appendix).

Subsequently, each participant performed three calibration trials to estimate the GH joint center using the following functional methods (Monnet et al., 2007): shoulder flexion/extension, abduction/adduction, and circumduction.

Participants performed the two different speeds of elevation trials in the frontal plane as follows: the slow and fast conditions were defined as 40 bpm and 120 bpm for the elevation and lowering speeds, respectively. The slow condition's speed is commonly used in the scapular dyskinesis test for the dynamic evaluation of the scapula (Matsuki et al., 2011; Sugamoto et al., 2002). In contrast, the fast condition's speed was decided to enable the participants to move as fast as possible with adjustments to the metronome's tempo (Prinold et al., 2013). The participants repeatedly practiced five reciprocating bilateral shoulder abduction–adduction movements from the resting position to 90°, with task speed controlled using a metronome. After becoming familiarized with the metronome tempo, each velocity condition was recorded during the experimental trials. Participants were verbally instructed to perform the arm elevation within the frontal plane prior to measurement. If there was a clear deviation from this plane, the motion was corrected before proceeding with the measurement. During the measurement, the examiner visually ensured that the motion was performed within the frontal plane. The reciprocating movement was conducted in neutral humeral rotation with full elbow extension while the participants held a weight equivalent to 2% of their body weight. The five reciprocating shoulder abduction–adduction movements were considered as one trial. The order of the conditions was adjusted with a counterbalance between the participants.

2.3. Data processing

The position coordinates of all markers were filtered using a fourth-order zero-lag Butterworth digital low-pass filter with a cut-off frequency of 10Hz. To analyze the posture of the humerus, scapula, and thorax during arm elevation, a local coordinate system was created based on the ISB recommendations (Wu et al., 2005). Humeral rotations relative to the trunk (humerothoracic angle: HT angle) and scapula (glenohumeral angle: GH angle), and the scapular rotation angle relative to the trunk (scapulothoracic joint angle: ST angle) were calculated using the Euler angle. The rotational sequence was determined using the ISB recommendations (Wu et al., 2005). To facilitate understanding, the upward rotation of the ST angle and the elevations of the HT and GH angles were represented as positive values. The angular velocities of the sagittal axis for the HT, GH, and ST joints were calculated using the time derivative of each angle and defined as the HT, GH, and ST angular velocities, respectively.

The SHR was defined as the ratio of GH angle to ST angle movement during arm elevation. This study defined the resting posture as HT0° and the resting angle offset the HT and ST joint angles, followed by the modified HT and ST angles (mHT and mST) were used to calculate SHR. The maximum mHT angle for several participants was <90° due to the resting offset. Therefore, the SHR could only be calculated up to 80°. Since many previous studies calculated SHR in 10° increments from the resting position (K. W. Lee et al., 2016; S. K. Lee et al., 2013; Yoshida et al., 2022), the equation of SHR is as follows.

$$SHR_i = (mHT_i - mST_i)/mST_i$$

$$mHT_i = HT_{i+rest} - HT_{rest} \ (i = 10, 20, 30, \ldots 80)$$

$$mST_i = ST_j - ST_{rest} \ (j = HT_{i+rest})$$

To calculate SHRi, we initially extracted the data closest to the angle of the HT angle increased by i° in the mHT, and mSTi was defined as the mST angle from the resting position to the ST angle at HT_{i+rest}. Therefore, SHRi was defined as the SHR from the resting position to each HT elevation position.

Since the abduction movement was this study's focus, only the abduction movements among the five abduction–adduction cycles were extracted for data analysis. The duration of interest was defined as the first positive value of the HT angular velocity (abduction movement) to the end of the abduction movement. Additionally, the abduction movement data were time-normalized from 0% to 100% elevation phase, and the first and second of the five cycles were excluded because some unstable parts were included in the angular velocities to catch up with the metronome. Each participant's representative values were calculated as the average of three abduction data. An outlier was defined as a cycle including the peak HT angular velocity that was not within three standard deviations of the mean across all participants in each condition (slow and fast conditions). To validate speed control, we calculated the time intervals between elevation angle peaks for all participants in each trial. Additionally, to confirm the plane of elevation, the horizontal adduction-abduction angle of the humerothoracic joint was calculated at 10° increments from the resting position for both the slow and fast conditions (Supplemental materials for the validation of each trial).

The average values of GH and ST angular velocities among all participants were plotted in a cyclogram, where the ST and GH angular velocities were the horizontal and vertical axes, respectively. Next, to compare the motion order between the GH and ST joints, the timings of peak GH and ST angular velocities of each participant were calculated in the elevation phase. Additionally, to analyze the characteristics in the setting phase, we extracted the GH and ST angular velocities from HT0° to HT30° and normalized them using the HT angle. Furthermore, to show the difference between conditions, the ratio of the average angular velocities (GH angular velocity/ST angular velocity) during the corresponding angular interval was calculated for HT0–10, HT10–20, and HT20–30, respectively.

2.4. Statistics

An a priori power analysis (a = 0.05, 1-β = 0.80) was performed to determine the sample size using G*Power (Version 3.1.9.4 Kiel University, Germany). We estimated that a sample size of 52 shoulders would be adequate to determine significant interaction effect between the condition and joint factors based on the large effect size of $\eta^2 = 0.14$ (Cohen J 1973).

All variables were normally distributed based on normality testing using the Shapiro–Wilk test. A three-way analysis of variance (ANOVA) was performed to examine the main effects of speed condition, dominant/non-dominant side, and HT angles on SHRs and to compare the timing of peak angular velocities of the GH and ST joints between the two conditions, sides, and joints. When a significant interaction effect was found from three-way ANOVA, we conducted post hoc t-tests with Bonferroni corrections. The differences in SHRs between the two conditions in each HT-angle were performed by the paired t-tests. SHRs in the HT-angles in each condition were also compared using a one-way repeated-measures ANOVA. The timings of peak angular velocities for each joint were compared in each condition using paired t-tests with the Bonferroni correction as the post hoc test of three-way ANOVA. All statistical analyses were performed using JMP Pro16 (SAS Institute Inc., Cary, NC). Finally, for the angle normalized angular velocity between joints, a one-dimensional statistical parametric mapping (SPM) two-tailed paired *t*-test was used to identify the HT angle where a significant difference occurred between the GH and ST joints in each condition. SPM analyses (Pataky, 2012) were conducted using the open-source code (spm1d: http://www.spm1d.org) in Python 3.9.13.

3. Results

Fifty-two shoulders from 26 healthy male participants were initially included in the study (age: 23.4 ± 2.9 years; height: 175.2 ± 6.3 cm; weight: 69.3 ± 8.4 kg). None of the participants were actively engaged in sports during the study period. However, some had prior experience in competitive sports: 13 in baseball, 2 in tennis, 1 in handball, 2 in football, and 4 in basketball. In the data analysis process, five participants were excluded due to the partial invisibility of AMC markers during the elevation trial, leaving 42 shoulders from 21 participants for the final analyses. Even after excluding missing data, the sample size was deemed adequate to determine the significant interaction and main effects of three-way ANOVA.

The results of the three-way ANOVA with the condition factor and the HT-angle factor showed a significant interaction effect ($\eta^2 = 0.126$, $p < .010$; Fig. 2), and main effects for both the condition ($\eta^2 = 0.094$, $p < .010$) and HT-angle ($\eta^2 = 0.112$, $p < .010$) factors. The significant interaction effect indicated that the pattern of the SHR across HT-angle conditions in the slow condition differed from that in the fast condition. Specifically, the SHR progressively decreased with arm elevation in the slow condition ($\eta^2 = 0.190$, $p < .010$; Fig. 2) but gradually increased in the fast condition ($\eta^2 = 0.080$, $p < .010$; Fig. 2). Furthermore, SHRs at HT10–30° for the slow condition were significantly higher than those for the fast condition (Cohen's d = 0.83, 0.85, and 0.69 and $p < .010$, $p < .010$, and $p = .034$, respectively). The mean (±SD) of the overall SHRs from resting position to 80° abduction for the slow and fast conditions were 1.19 ± 0.50 and 1.48 ± 0.66, respectively. In the side factor, there is no significant interaction with condition or HT-angle factors, also no significant main effect was observed.

The trajectory of each cyclogram differed between the two conditions (Fig. 3). In the slow condition, the GH angular velocity was larger than the ST angular velocity in the 0–25% elevation phase; however, those magnitudes were reversed after the 25% elevation phase, resulting in the cyclogram showing a clockwise trajectory. The ST angular velocity exceeded the GH angular velocity from 0% to 50% elevation phase in the fast condition. Subsequently, the GH angular velocity remained at higher speed in the 50–75% elevation phase, while the ST angular velocity decelerated during the phase. Moreover, the magnitudes of the GH and ST angular velocities were reversed during the ST angular velocity deceleration phase. Consequently, the trajectory was counterclockwise, contrary to the slow condition.

The peak angular velocity of the GH joint was earlier than that of the ST joint in the slow condition but later in the fast condition (Table 1). A significant interaction effect was found between the condition and joint factors (η2 = 0.219, p < .010); otherwise, we found no significant interaction between side factors and condition or joint factors. The timing of the peak GH joint angular velocity was significantly earlier than that of the ST joint in the slow condition (Cohen's d = 0.61, $p < .010$; Table 1), while it was later than that in the fast condition (Cohen's d = 0.98, $p < .010$; Table 1).

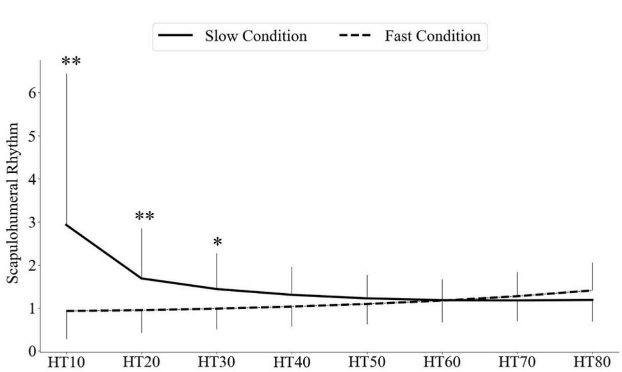

Fig. 2. — Mean and standard deviation of the scapulohumeral rhythm for the slow and fast conditions for each increment in the humerothoracic angle. *Significant differences between the speed conditions (*p < .05, **p < .01).

In the slow condition, a significantly larger GH angular velocity than the ST angular velocity was observed in 4–6° HT angles ($p < .050$; Fig. 4), and these reversed after a 20° HT angle ($p < .010$; Fig. 4). The ST angular velocity was significantly larger than the GH angular velocity at a 2–30° HT angle in the fast condition. Furthermore, in the slow condition, the ratio of the average angular velocities (GH angular velocity/ST angular velocity) showed over '1' during the corresponding angular interval for HT0–10 and HT10–20, and the standard deviation of HT0–10 was larger than those of other intervals (Table 2).

4. Discussion

This study assessed the dynamic coordination of the GH and ST joints to clarify the differences in the features under high and low arm elevation speed. We hypothesized that the coordinated movement of the GH and ST joints based on the angular velocity would be characterized by elevation speed. The cyclogram of the GH and ST joint angular velocities indicated that the GH angular velocity exceeded the ST angular velocity in the 0–25% elevation phase, and the analysis in the setting phase showed that the GH angular velocity was significantly higher than the ST angular velocity in 4–6° HT angles (Figs. 3 and 4). In contrast, the angular velocity of the ST joint was higher than that of the GH joint from the beginning of arm elevation in the fast condition (Fig. 4). However, it gradually decreased in the middle elevation phase while the GH angular velocity maintained a higher value during the phase (Fig. 3). Therefore, the motion order was ST to GH, which differed from that of the slow condition (Table 1).

Some previous studies showed that the SHR in the early elevation phase was larger than that in the latter phase (Chung et al., 2019; Kijima et al., 2015; Sugamoto et al., 2002). Consistent with the previous studies, the SHR in the slow condition in this study was larger in the early phase and progressively decreased with arm elevation (Fig. 2). Similar to the results, the ST angular velocity became significantly higher than the GH angular velocity from a 20° HT angle (Fig. 4). It is established that the lower and middle trapezius activities, functioning as the force couple of the scapular movement, are activated higher from ≥30° shoulder abduction than at the resting position (Pizzari et al., 2014). Using this evidence, the Watson Instability Program (WIP1) was developed and recognized as one of the effective rehabilitation programs for multidirectional instability, emphasizing the acquisition of scapular upward rotation at 20–30° shoulder abduction (Pizzari et al., 2014; Warby et al., 2018; Watson et al., 2016). Therefore, our results provided evidence from the biomechanical analysis viewpoint and might help understand normal shoulder joint movement, which is useful for rehabilitating shoulder joint injuries.

Our results from the angular velocities in slow condition indicated that two phases existed within the setting phase. The first phase ranged from the resting position to approximately 10° of HT angle, where both angular velocities drastically increased (Fig. 4). In this phase, the standard deviation of the ratio of the average angular velocity in the HT0–10 interval of slow condition was significantly larger than that in the other intervals (Table 2), similar to the previous study (Umehara et al., 2019). For the second phase, the change of the angular velocities of the GH and ST joints were gentle (Fig. 4). In this phase, the standard deviation of the ratio of average angular velocities among the participants was settled (Table 2). According to these results, although the setting phase is generally defined as the first phase during HT0-30° (Inman et al., 1944), this angle is likely to vary between participants. A previous study using the finite model reported that the increase in upward migration of the humeral head was observed in the model with the supraspinatus deficiency, particularly at the beginning of the arm elevation. The finding implies that the positional relationship between the glenoid and the humeral head is highly variable in the phase and that the phase can affect the mechanical stress at the GH joint (Terrier et al., 2007).

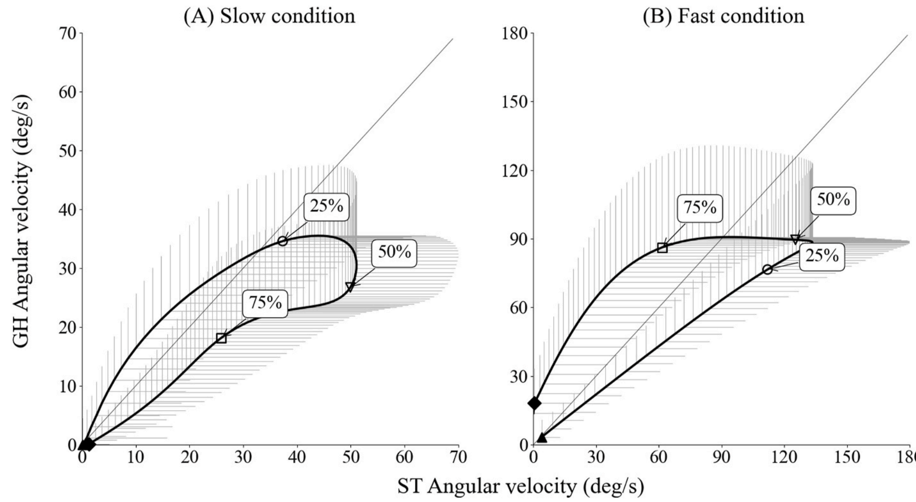

Fig. 3. — The cyclogram of the glenohumeral and scapulothoracic joint angular velocities during the elevation cycle. (A) Slow condition. (B) Fast condition. Solid bold black lines show means. Thin grey vertical and horizontal lines show standard deviations. ▲ (triangle): 0% of the elevation cycle. ○ (white circle): 25% of the elevation cycle. □ (white square): 50% of the elevation cycle. △ (white triangle): 75% of the elevation cycle. ◆ (diamond): 100% of the elevation cycle. Diagonal lines indicate the X = Y (ST angular velocity = GH angular velocity).
Abbreviations: ST, scapulothoracic; GH, glenohumeral.

Table 1
Mean and standard deviation of the timing of peak angular velocities during the elevation cycle for the glenohumeral (GH) and scapulothoracic (ST) joints in each condition. p-values were calculated using the post hoc t-tests between segments and between conditions. Units of the result were %elevation phase.

	Slow condition	Fast condition	p-value
GH angular velocity	35.0 ± 16.9	54.2 ± 18.4	<0.01
ST angular velocity	43.2 ± 8.3	40.8 ± 5.6	n.s.
p-value	<0.01	<0.01	

Therefore, analyzing the inter-joint coordination of GH and ST joints during the setting phase may help identify the development of shoulder joint injuries for future study.

The ST angular velocity was higher than the GH angular velocity from the beginning of arm elevation for the fast condition (Figs. 3 and 4), and the timing of peak angular velocity was in the order of ST to GH (Table 1). Additionally, during the 50–75% elevation phase, the ST angular velocity value decelerated while the GH angular velocity remained high (Fig. 3). These results indicated that the characteristics of inter-joint coordination in the fast condition were similar to a proximal-to-distal sequence pattern (PDS) (Putnam, 1993). Previous studies on the relationship between external load and the ST joint movement have shown that an increase in external load affects inter-joint coordination (Madokoro et al., 2016). The ST joint upward rotation was shifted to the earlier elevation phase as the external load increased. In the current

Table 2
Mean and standard deviation of the ratio of the average angular velocity (glenohumeral angular velocity/scapulothoracic angular velocity) in humerothoracic angle (HT) 0–10°, 10–20°, and 20–30°.

	Slow condition	Fast condition
HT 0–10°	2.34 ± 3.80	0.77 ± 0.59
HT 10–20°	1.00 ± 0.67	0.70 ± 0.52
HT 20–30°	0.79 ± 0.62	0.68 ± 0.54

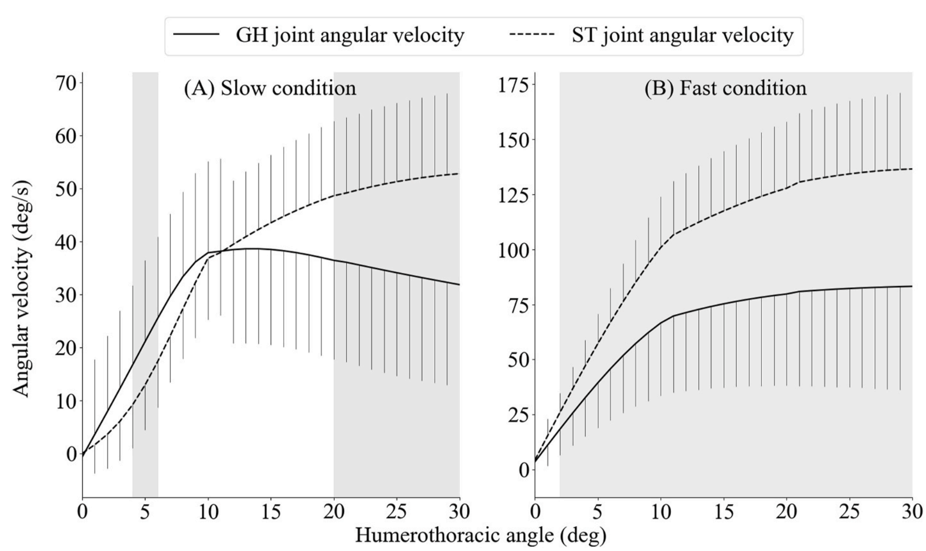

Fig. 4. — The result of statistical parametric mapping. Solid and dashed lines are the mean glenohumeral and mean scapulothoracic joint angular velocities, respectively. Vertical lines show the standard deviations. Grey regions are the range of significant differences between joints. (A) Slow condition. (B) Fast condition.

study, the external load did not change; however, the increase in speed could function similarly to that with the increase in the external load. Combined with the previous study, the increase in the intensity of movement may cause the ST joint to move earlier. Additionally, a study that examined PDS in a pitching motion showed that the motion order was from scapula to humerus (Yanai et al., 2023), similar to that of this study where a simple movement was employed. Consequently, this feature might be one of the characteristics of inter-joint coordination of high-speed movements. Furthermore, the role of the ST joint in the inter-joint coordination of shoulder joint complex in high-speed motion suggested that the scapula, as the proximal segment, played a role in accelerating the humerus which is the distal segment.

Several systematic reviews have shown that scapular exercises are effective for shoulder impingement syndrome (Ravichandran et al., 2020). In addition to improving joint range of motion and strengthening the scapular muscles (Nodehi Moghadam et al., 2020), stabilization training has been reported to be necessary. However, no reports have addressed the speed of the exercises. This study's results indicated that the required function of the ST joint differs between the slow and fast movements. Therefore, variations in training, such as varying the task speed, may be more effective for improving the ST joint function. Moreover, future studies on the effects of varying exercise speeds on the ST joint function and scapular kinematics may provide effective interventions for shoulder joint injuries.

This study had some limitations. First, the of the elevation plane for each condition may have been insufficient. Although the plane was visually monitored during measurements, it is possible that a deviation of approximately 10° in the plane of elevation was allowed. This deviation was particularly larger at lower elevation angles, where it might have been difficult to judge accurately through visual observation alone. Future studies should explore more precise methods for controlling the plane of elevation. Although the elevation plane was significantly more anterior in the slow condition compared to the fast condition, a previous study has shown no effect of the elevation plane on scapular upward rotation when comparing shoulder abduction and flexion movements (Ludewig PM et al., 2009). Therefore, the differences in elevation plane between conditions in the present study were considered to be within an acceptable range that would not meaningfully impact the results. Second, the AMC method is associated with measurement errors due to skin motion artifacts (Konda et al., 2018; Matsui et al., 2006; Shaheen et al., 2011). However, previous studies have shown that the accuracy of the AMC method is reasonably <120° of arm elevation (Chu et al., 2012). Moreover, an ultrasonography device was used to measure the position of the AA at calibration. This modality minimized skin motion artifacts by accurately identifying the AA and canceling out the subcutaneous tissue's thickness. The importance of analyzing shoulder movement during arm elevation above 90° is emphasized, as shoulder problems are often associated with overhead arm movements in sports activity. This study's methodology, which involves calibration using an ultrasonography device, may help overcome skin motion artifacts during the analysis of higher elevation phases. Third, this study involved healthy male participants. The characteristics of female participants or injured individuals are unclear. Therefore, the characteristics of inter-joint coordination of shoulder complex joint observed in this study, such as the ST joint acting ahead of the GH joint under the fast condition, cannot be conclusively determined as abnormal or not. Future studies involving participants with different attributes, such as females or individuals with injuries, are needed to better understand these findings. Lastly, only the shoulder abduction task was analyzed; therefore, whether other movements would demonstrate the same trend remains unclear. Furthermore, the analysis was limited to the frontal plane, leaving the effect of arm elevation speed on other planes of elevation unclear. Despite these limitations, this study provides data that could support a biomechanical basis for established rehabilitation programs, as well as basic data that could be applied to sports movements in high-speed movements. Therefore, we believe that these findings contribute to a better understanding of normal shoulder joint motion and will serve as essential baseline data for future research.

5. Conclusion

The angular velocities of the GH and ST joints during arm elevation under two different speed conditions were analyzed to clarify the characteristics of inter-joint coordination in shoulder movement. In the slow condition, GH joint motion was larger than ST joint motion at the beginning of arm elevation, and the contributions of the GH and ST joints shifted as the HT angle increased during the setting phase. These results suggest that two distinct phases exist within the setting phase, each characterized by different GH and ST joint contributions, which could support established rehabilitation programs from a biomechanical perspective. Furthermore, although the setting phase is generally defined as the first phase during HT0-30°, this angle is likely to vary between participants. Therefore, the inter-joint coordination of the shoulder joint complex may affect the development of shoulder joint injuries. Otherwise, in the fast condition, the increased intensity of movement caused the ST joint to engage earlier, with inter-joint coordination for fast arm elevation following a proximal-distal sequence pattern. These findings provide valuable insights into the quantitative assessment of GH and ST joint coordination and highlight the necessity for the variation in scapular training to effectively rehabilitate shoulder disorders for overhead motion like a sports activity.

5.1. Clinical relevance

- The arm elevation speed affected the coordinated patterns of glenohumeral and scapulothoracic joint motion. Therefore, varying the speed of movement should be considered as part of rehabilitation objectives.
- The results of the angular velocities in the slow condition revealed two distinct phases within the setting phase, with variation observed among participants. These findings may provide evidence for designing rehabilitating programs aimed at alleviating shoulder joint pain during the initial phase of arm elevation, from a biomechanical perspective.
- In the fast condition, the scapulothoracic joint needs to engage earlier. To improve scapulothoracic joint function in response to shoulder joint injuries, particularly in overhead sports, training programs may need to incorporate variations such as adjusting task speed.

CRediT authorship contribution statement

Tomoya Uchida: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tomoyuki Matsuo:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Issei Ogasawara:** Writing – review & editing. **Shoji Konda:** Writing – review & editing. **Hiroyuki Tanaka:** Writing – review & editing. **Ken Nakata:** Writing – review & editing, Supervision.

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Declaration of competing interest

All authors declare there are no conflicts of interest.

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Appendix A. Supplementary data

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References

Bourne, D.A., Choo, A.M., Regan, W.D., MacIntyre, D.L., Oxland, T.R., 2009. A new subject-specific skin correction factor for three-dimensional kinematic analysis of the scapula. J. Biomech. Eng. 131, 121009. https://doi.org/10.1115/1.4000284.

Brochard, S., Lempereur, M., Rémy-Néris, O., 2011. Double calibration: an accurate, reliable and easy-to-use method for 3D scapular motion analysis. J. Biomech. 44, 751–754. https://doi.org/10.1016/j.jbiomech.2010.11.017.

Chiu, S.L., Chou, L.S., 2012. Effect of walking speed on inter-joint coordination differs between young and elderly adults. J. Biomech. 45, 275–280. https://doi.org/10.1016/j.jbiomech.2011.10.028.

Chu, Y., Akins, J., Lovalekar, M., Tashman, S., Lephart, S., Sell, T., 2012. Validation of a video-based motion analysis technique in 3-D dynamic scapular kinematic measurements. J. Biomech. 45, 2462–2466. https://doi.org/10.1016/j.jbiomech.2012.06.025.

Chung, H.J., Kim, D.S., Banks, S.A., Son, J.S., Kim, Y.H., On, M.G., Yeom, J.S., 2019. Evaluation of three-dimensional in vivo scapular kinematics and scapulohumeral rhythm between shoulders with a clavicle hook plate and contralateral healthy shoulders. Int. Orthop. 43, 379–386. https://doi.org/10.1007/s00264-018-4003-y.

Cohen, J., 1973. Eta-squared and partial eta-squared in fixed factor ANOVA designs. Educ. Psychol. Meas. 33, 107–112. https://doi.org/10.1177/001316447303300111.

Forte, F.C., Peduzzi de Castro, M., Mahnic de Toledo, J., Ribeiro, D.C., Loss, J.F., 2009. Scapular kinematics and scapulohumeral rhythm during resisted shoulder abduction - implications for clinical practice. Phys. Ther. Sport 10, 105–111. https://doi.org/10.1016/j.ptsp.2009.05.005.

Huang, T.S., Huang, H.Y., Wang, T.G., Tsai, Y.S., Lin, J.J., 2015. Comprehensive classification test of scapular dyskinesis: a reliability study. Man. Ther. 20, 427–432. https://doi.org/10.1016/j.math.2014.10.017.

Inman, V.T., Saunders, J.B., Abbott, L.C., 1944. Observations of the function of the shoulder joint. J. Bone Joint Surg. 26, 1–30. https://doi.org/10.1097/00003086-199609000-00002.

Kibler, W., Ben Uhl, T.L., Maddux, J.W.Q., Brooks, P.V., Zeller, B., McMullen, J., 2002. Qualitative clinical evaluation of scapular dysfunction: a reliability study. J. Shoulder Elbow Surg. 11, 550–556. https://doi.org/10.1067/mse.2002.126766.

Kijima, T., Matsuki, K., Ochiai, N., Yamaguchi, T., Sasaki, Y., Hashimoto, E., Sasaki, Y., Yamazaki, H., Kenmoku, T., Yamaguchi, S., Masuda, Y., Umekita, H., Banks, S.A., Takahashi, K., 2015. In vivo 3-dimensional analysis of scapular and glenohumeral kinematics: comparison of symptomatic or asymptomatic shoulders with rotator cuff tears and healthy shoulders. J. Shoulder Elbow Surg. 24, 1817–1826. https://doi.org/10.1016/j.jse.2015.06.003.

Kon, Y., Nishinaka, N., Gamada, K., Tsutsui, H., Banks, S.A., 2008. The influence of handheld weight on the scapulohumeral rhythm. J. Shoulder Elbow Surg. 17, 943–946. https://doi.org/10.1016/j.jse.2008.05.047.

Konda, S., Sahara, W., Sugamoto, K., 2018. Directional bias of soft-tissue artifacts on the acromion during recording of 3D scapular kinematics. J. Biomech. 73, 217–222. https://doi.org/10.1016/j.jbiomech.2018.03.005.

Lee, H.S., Ryu, H., Lee, S.U., Cho, J.S., You, S., Park, J.H., Jang, S.H., 2021. Analysis of gait characteristics using hip-knee cyclograms in patients with hemiplegic stroke. Sensors 21. https://doi.org/10.3390/s21227685.

Lee, K.W., Kim, Y.I., Kim, H.Y., Yang, D.S., Lee, G.S., Choy, W.S., 2016. Three-dimensional scapular kinematics in patients with reverse total shoulder arthroplasty during arm motion. Clin. Orthop. Surg. 8, 316–324. https://doi.org/10.4055/cios.2016.8.3.316.

Lee, S.K., Yang, D.Y., Kim, H.Y., Choy, W.S., 2013. A comparison of 3D scapular kinematics between dominant and nondominant shoulders during multiplanar arm motion. Indian J. Orthop. 47, 135–142. https://doi.org/10.4103/0019-5413.108882.

Longworth, J.A., Chlosta, S., Foucher, K.C., 2018. Inter-joint coordination of kinematics and kinetics before and after total hip arthroplasty compared to asymptomatic subjects. J. Biomech. 72, 180–186. https://doi.org/10.1016/j.jbiomech.2018.03.015.

Ludewig, P.M., Phadke, V., Braman, J.P., Hassett, D.R., Cieminski, C.J., LaPrade, R.F., 2009. Motion of the shoulder complex during multiplanar humeral elevation. J. Bone Jt. Surg. Am. 91, 378–389. https://doi.org/10.2106/JBJS.G.01483.

Madokoro, K., Gotoh, M., Kai, Y., Kakuma, T., Nagamatsu, T., Shiba, N., 2016. Effect of external load on scapular upward rotation during arm elevation: the knot concept. J. Exp. Orthop. 3, 1–7. https://doi.org/10.1186/s40634-016-0044-6.

Matsui, K., Shimada, K., Andrew, P.D., 2006. Deviation of skin marker from bone target during movement of the scapula. J. Orthop. Sci. 11, 180–184. https://doi.org/10.1007/s00776-005-1000-y.

Matsuki, K., Matsuki, K.O., Mu, S., Yamaguchi, S., Ochiai, N., Sasho, T., Sugaya, H., Toyone, T., Wada, Y., Takahashi, K., Banks, S.A., 2011. In vivo 3-dimensional analysis of scapular kinematics: comparison of dominant and nondominant shoulders. J. Shoulder Elbow Surg. 20, 659–665. https://doi.org/10.1016/j.jse.2010.09.012.

McClure, P., Tate, A.R., Kareha, S., 2009. A clinical method for identifying scapular dyskinesis, part 1: reliability. J. Athl. Train. 44, 160–164. https://doi.org/10.4085/1062-6050-44.2.160.

Monnet, T., Desailly, E., Begon, M., Vallée, C., Lacouture, P., 2007. Comparison of the SCoRE and HA methods for locating in vivo the glenohumeral joint centre. J. Biomech. 40, 3487–3492. https://doi.org/10.1016/j.jbiomech.2007.05.030.

Nodehi Moghadam, A., Rahnama, L., Noorizadeh Dehkordi, S., Abdollahi, S., 2020. Exercise therapy may affect scapular position and motion in individuals with scapular dyskinesis: a systematic review of clinical trials. J. Shoulder Elbow Surg. 29, e29–e36. https://doi.org/10.1016/j.jse.2019.05.037.

Park, J.H., Lee, H., Cho, J.S., Kim, I., Lee, J., Jang, S.H., 2021. Effects of knee osteoarthritis severity on inter-joint coordination and gait variability as measured by hip-knee cyclograms. Sci. Rep. 11. https://doi.org/10.1038/s41598-020-80237-w.

Pataky, T.C., 2012. One-dimensional statistical parametric mapping in Python. Comput. Methods Biomech. Biomed. Eng. 15, 295–301. https://doi.org/10.1080/10255842.2010.527837.

Pizzari, T., Wickham, J., Balster, S., Ganderton, C., Watson, L., 2014. Modifying a shrug exercise can facilitate the upward rotator muscles of the scapula. Clin. BioMech. 29, 201–205. https://doi.org/10.1016/j.clinbiomech.2013.11.011.

Prinold, J.A.I., Villette, C.C., Bull, A.M.J., 2013. The influence of extreme speeds on scapula kinematics and the importance of controlling the plane of elevation. Clin. BioMech. 28, 973–980. https://doi.org/10.1016/j.clinbiomech.2013.10.008.

Putnam, C.A., 1993. Sequential motions of body segments in striking and throwing skills: descriptions and explanations. J. Biomech. 26, 125–135.

Ravichandran, H., Janakiraman, B., Gelaw, A.Y., Fisseha, B., Sundaram, S., Sharma, H.R., 2020. Effect of scapular stabilization exercise program in patients with subacromial impingement syndrome: a systematic review. J. Exerc. Rehabil. 16, 216–226. https://doi.org/10.12965/jer.2040256.128.

Seitz, A.L., McClure, P.W., Lynch, S.S., Ketchum, J.M., Michener, L.A., 2012. Effects of scapular dyskinesis and scapular assistance test on subacromial space during static arm elevation. J. Shoulder Elbow Surg. 21, 631–640. https://doi.org/10.1016/j.jse.2011.01.008.

Shaheen, A.F., Alexander, C.M., Bull, A.M.J., 2011. Effects of attachment position and shoulder orientation during calibration on the accuracy of the acromial tracker. J. Biomech. 44, 1410–1413. https://doi.org/10.1016/j.jbiomech.2011.01.013.

Sugamoto, K., Harata, T., Machida, A., Inui, H., Miyamoto, T., Takeuchi, E., Yoshikawa, H., Ochi, T., 2002. Scapulohumeral rhythm: relationship between motion velocity and rhythm. Clin. Orthop. Relat. Res. 401, 119–124. https://doi.org/10.1097/00003086-200208000-00014.

Tate, A.R., Mcclure, P., Kareha, S., Irwin, D., Barbe, M.F., 2009. A clinical method for identifying scapular dyskinesis, part 2: validity. J. Athl. Train. 44, 165–173. https://doi.org/10.4085/1062-6050-44.2.165.

Terrier, A., Reist, A., Vogel, A., Farron, A., 2007. Effect of supraspinatus deficiency on humerus translation and glenohumeral contact force during abduction. Clin. BioMech. 22, 645–651. https://doi.org/10.1016/j.clinbiomech.2007.01.015.

Umehara, J., Yagi, M., Hirono, T., Komamura, T., Nishishita, S., Ichihashi, N., 2019. Relationship between scapular initial position and scapular movement during dynamic motions. PLoS One 14, e0227313. https://doi.org/10.1371/journal.pone.0227313.

Walker, D., Matsuki, K., Struk, A.M., Wright, T.W., Banks, S.A., 2015. Scapulohumeral rhythm in shoulders with reverse shoulder arthroplasty. J. Shoulder Elbow Surg. 24, 1129–1134. https://doi.org/10.1016/j.jse.2014.11.043.

Warby, S.A., Ford, J.J., Hahne, A.J., Watson, L., Balster, S., Lenssen, R., Pizzari, T., 2018. Comparison of 2 exercise rehabilitation programs for multidirectional instability of the glenohumeral joint: a randomized controlled trial. Am. J. Sports Med. 46, 87–97. https://doi.org/10.1177/0363546517734508.

Watson, L., Warby, S., Balster, S., Lenssen, R., Pizzari, T., 2016. The treatment of multidirectional instability of the shoulder with a rehabilitation program: Part 1. Shoulder Elbow 8, 271–278. https://doi.org/10.1177/1758573216652086.

Wu, G., Van Der Helm, F.C.T., Veeger, H.E.J., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A.R., McQuade, K., Wang, X., Werner, F.W., Buchholz, B., 2005. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - Part II: shoulder, elbow, wrist and hand. J. Biomech. 38, 981–992. https://doi.org/10.1016/j.jbiomech.2004.05.042.

Yanai, T., Crotin, R., Du, T., 2023. Proximal to distal sequencing impacts on maximum shoulder joint angles and the risk of impingement in baseball pitching involving a scapular independent thoracohumeral model. Scand. J. Med. Sci. Sports 33, 1322–1334. https://doi.org/10.1111/sms.14374.

Yoshida, Y., Matsumura, N., Miyamoto, A., Oki, S., Yokoyama, Y., Yamada, M., Yamada, Y., Nakamura, M., Nagura, T., Jinzaki, M., 2022. Three-dimensional shoulder kinematics: upright four-dimensional computed tomography in comparison with an optical three-dimensional motion capture system. J. Orthop. Res. 41, 196–205. https://doi.org/10.1002/jor.25342.