Original Research

Stress Distribution Patterns Across the Shoulder Joint in Gymnasts

A Computed Tomography Osteoabsorptiometry Study

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Background: The distribution pattern of subchondral bone density is an indicator of stress distribution over a joint surface under long-term physiologic loading. The biomechanical characteristics of the articular surfaces of the shoulder joint in gymnasts can be determined by measuring this distribution pattern.

Purpose: To evaluate the distribution of subchondral bone density across the shoulder joint in male collegiate gymnasts and to determine the effects of gymnastic activities on its articular surfaces under long-term loading conditions using computed tomography osteoabsorptiometry (CTOAM).

Study Design: Descriptive laboratory study.

Methods: CT image data were obtained from both shoulders of 12 asymptomatic male collegiate gymnasts (gymnast group; mean age, 19.4 years; range, 18-22 years) and 10 male collegiate volunteers (control group; mean age, 20.2 years; range, 18-22 years). The distribution pattern of subchondral bone density across the articular surfaces of each shoulder joint was assessed by CTOAM. Quantitative analysis was performed of the locations and percentages of high-density areas on the articular surface.

Results: Stress distribution patterns over the articular surfaces differed between the gymnasts and the controls. In the gymnasts, high-density areas were detected on the posterosuperior articular surface of the humeral head and the anterosuperior and/or posterosuperior articular surface of the glenoid. Mean bone density was greater in the gymnasts than in the controls ($P < .0001$).

Conclusion: Stress distribution over the articular surfaces of the shoulder joint was affected by gymnastic activities. Stress was concentrated over the superior part of the glenohumeral joint in male collegiate gymnasts.

Clinical Relevance: The present findings suggest that gymnastic activities increase stress to the articular surfaces of the superior glenohumeral joint. This supports the notion that mechanical conditions play a crucial role in the origin of disorders particular to gymnastic activities.

Keywords: gymnast; shoulder; CT osteoabsorptiometry; stress distribution

According to USA Gymnastics, approximately 4.8 million recreational athletes and 85,000 competitive athletes participate in gymnastics annually in the United States.[29] Gymnasts frequently sustain severe injuries such as fractures and dislocations, the majority of which involve the upper extremities.[6] Of these, the shoulder is the most frequently injured site, followed by the elbow. Because gymnastic activities expose the shoulder to repetitive motion, high-impact loading, axial compression, torsional forces, and distraction and combine these forces with varying degrees of glenohumeral joint position, the shoulder is predisposed to high rates of injury.[13]

The prevalence of shoulder pain among high-level club and collegiate gymnasts is 17%, and the injury rate of the shoulder is higher in male gymnasts.[5,11,32] The shoulder can be subjected to forces up to 8.5 times body weight during gymnastic activities.[4] Chronic shoulder pain in young gymnasts generally worsens with weightbearing and extension. To better understand the causes and prevention of such injuries and disorders, it is necessary to elucidate the biomechanical characteristics of the shoulder under the actual loading conditions of gymnastic activities.

Repetitive mechanical stress acting on the shoulder is considered to be a cause of pathological conditions. To date, several biomechanical and cadaveric studies have examined ligament tension around the shoulder during gymnastic activities.[9,23,25,30] However, few biomechanical studies

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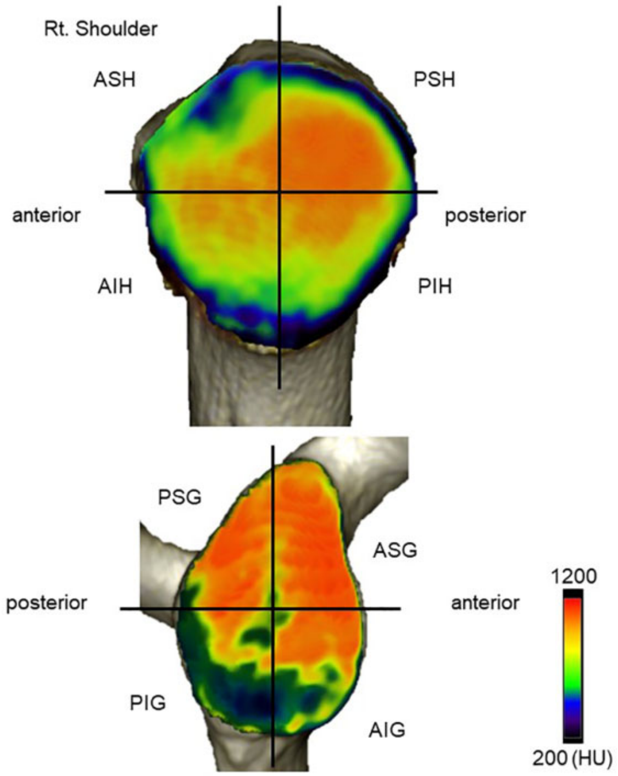

Figure 1. Regions used in quantitative analysis of the mapped computed tomography data. AIG, anteroinferior glenoid; AIH, anteroinferior humeral head; ASG, anterosuperior glenoid; ASH, anterosuperior humeral head; HU, Hounsfield unit; PIG, posteroinferior glenoid; PIH, posteroinferior humeral head; PSG, posterosuperior glenoid; PSH, posterosuperior humeral head; Rt, right.

are available regarding stress distribution through the articular surfaces of the shoulder joint during gymnastic activities, as it is difficult to measure and simulate actual loading conditions. For these reasons, the characteristics of stress distribution over the articular surfaces of gymnasts' shoulders are not well understood. To develop treatment and prevention strategies for the pathological conditions mentioned above, it is necessary to elucidate the biomechanical characteristics of the shoulder under the actual loading conditions of gymnastic activities.

The distribution of subchondral bone density is known to reflect the long-term resultant stresses acting on an articular surface in living joints.[20] Drawing on this theory, Müller-Gerbl et al[20,21] developed a method of measuring subchondral bone density using computed tomography (CT) image data, termed CT osteoabsorptiometry (CTOAM), to assess long-term stress distribution in living joints. Using this method, Momma et al[18] reported significantly different stress distribution through the wrist joints of gymnasts compared with nonathletes.

The aim of the current study was to assess the distribution of subchondral bone density across the humeral head and glenoid surface of the shoulder in highly competitive male collegiate gymnasts and nonathletic controls and to compare the stress distribution patterns between the 2 groups. We hypothesized that the bone mineral density distribution pattern would differ between the shoulders of the gymnasts versus the controls. To test this hypothesis, we conducted modified CTOAM on the articular surfaces of shoulder joints in the study participants.[14,19]

TABLE 1
Characteristics of the Study Participants

Group and Participant No.	Age, y	Dominance	Height, cm	Weight, kg
Control group				
C1	21	Right	162	51
C2	21	Right	171	60
C3	20	Right	173	60
C4	20	Right	163	58
C5	18	Right	161	53
C6	19	Right	170	61
C7	19	Right	170	63
C8	22	Right	178	67
C9	22	Right	169	63
C10	20	Right	159	60
Mean	20.2		167.6	59.6
Gymnast group				
G1	18	Right	159	52
G2	19	Right	163	57
G3	18	Right	173	65
G4	18	Right	165	62
G5	18	Right	167	58
G6	21	Right	165	59
G7	18	Right	162	59
G8	20	Right	164	54
G9	19	Right	160	57
G10	20	Right	162	58
G11	22	Right	164	55
G12	22	Right	165	55
Mean	19.4		164.1	57.6
P Value, control vs gymnast	.2240		.1076	.2650

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Ethical approval for this study was obtained from Hokkaido University Hospital (ref No. 018-0017).

TABLE 2
Bone Density and Mineralization Patterns of the Study Participants[a]

	Range of Bone Density, HU					
	Humeral Head		Glenoid		Mineralization Pattern	
Participant	Dominant	Nondominant	Dominant	Nondominant	Humeral Head	Glenoid
C1	202-1002	204-978	358-1409	215-1427	Bicentric	Bicentric
C2	311-767	308-890	329-1239	375-1182	Bicentric	Bicentric
C3	311-879	318-1133	310-1204	369-1237	Bicentric	Bicentric
C4	210-990	204-898	216-1198	346-1180	Bicentric	Bicentric
C5	209-905	204-898	356-1421	205-1276	Bicentric	Bicentric
C6	201-916	202-913	360-1262	249-1244	Bicentric	Bicentric
C7	209-917	210-891	218-1228	217-1210	Bicentric	Bicentric
C8	207-733	203-947	225-1416	330-1288	Bicentric	Bicentric
C9	201-726	159-821	369-1245	380-1293	Bicentric	Bicentric
C10	202-897	202-909	327-1358	362-1261	Monocentric	Monocentric
Range	201-1002	159-1133	216-1421	205-1427		
Mean ± SD	541.7 ± 64.6	531.0 ± 60.4	875.8 ± 63.1	854.8 ± 67.8		
P value, D vs ND	.7067		.4830			
G1	304-977	204-976	335-1412	365-1420	Monocentric	Monocentric
G2	201-964	203-932	241-1439	246-1461	Bicentric	Bicentric
G3	206-956	205-962	212-1268	205-1281	Bicentric	Bicentric
G4	255-1225	202-970	382-1330	237-1409	Monocentric	Monocentric
G5	206-913	205-876	363-1239	386-1209	Bicentric	Bicentric
G6	201-957	202-1173	210-1418	213-1419	Bicentric	Bicentric
G7	201-1164	201-1221	240-1441	211-1456	Monocentric	Monocentric
G8	204-966	201-973	386-1414	407-1383	Monocentric	Monocentric
G9	202-966	201-971	210-1360	202-1392	Monocentric	Monocentric
G10	302-964	309-998	379-1479	206-1445	Monocentric	Monocentric
G11	202-1097	201-1125	496-1462	203-1448	Monocentric	Monocentric
G12	205-978	210-987	202-1442	214-1437	Bicentric	Bicentric
Range	201-1225	201-1221	202-1479	202-1461		
Mean ± SD	624.2 ± 49.0	622.3 ± 63.4	1027.6 ± 65.7	1009.1 ± 81.5		
P value, D vs ND	.9369		.5479			
P value, C vs G	.0028	.0026	<.0001	.0001		

[a]C, control group; D, dominant; G, gymnast group; HU, Hounsfield unit; ND, nondominant.

METHODS

Acquisition of CT Image Data

Institutional review board approval was obtained before initiation of the study, and informed consent was obtained from all participants. In total, 12 male collegiate gymnasts (gymnast group; mean age, 19.4 years; range, 18-22 years) and 10 male collegiate volunteers (control group; mean age, 20.2 years; range, 18-22 years) underwent CT of both shoulders between October 2018 and March 2019. Body weight and height were also measured. All participants in both groups were volunteers with no shoulder symptoms or history of shoulder disorder or trauma. Those in the gymnast group had been on a gymnastics team since junior high school. The mean number of years they had participated in gymnastics was 7.4 years. Those in the control group had not played any sports in daily life since junior high school.

CT Osteoabsorptiometry

The CT image data were transferred to an image analyzing system (Revolution CT; GE Healthcare) for evaluation. A 3-dimensional bone model was created from the axial image data, and 1 mm–interval coronal views were then reconstructed from the model. Further evaluation was performed using a custom-designed software program.[8] On the coronal reconstruction images, a region of interest was manually selected that included the entire subchondral bone layer of the articular surfaces of the shoulder joint in all slices. After the region of interest was established, x-ray beam attenuation (measured in Hounsfield units [HU], defined as water = 0 and compact bone = 1000) was measured automatically at coordinate points at an interval of 1 mm. Measurement and mapping were repeated in each slice, and the data were stacked to create a 2-dimensional mapping image showing the distribution of subchondral bone density. The mean, maximum, and minimum bone density were measured for each joint surface, and the absolute values were compared for each group. The bone density distribution patterns of the humeral head and glenoid surface were classified as described previously.[33]

Quantitative Analysis of the Mapping Images

Quantitative analysis of the mapping images focused on the area and location of high density of each articular surface. Areas of HU >800 were termed high-density areas (HDAs).[15] The surface of the humeral head was divided into 4 parts, as follows: anterosuperior humeral head (ASH), posterosuperior humeral head (PSH), anteroinferior humeral head (AIH), and posteroinferior humeral head (PIH). The glenoid surface was also divided into 4 parts: anterosuperior glenoid (ASG), posterosuperior glenoid (PSG), anteroinferior glenoid (AIG), and posteroinferior glenoid (PIG) (Figure 1).

Two orthopaedic surgeons (D.M., W.I.) who were blinded to the group assignment measured the bone mineral density. The percentage of HDA (%HDA) was calculated for each part of the humeral head and glenoid, and the values were compared between the groups. Before analysis, intraobserver reproducibility of CTOAM was calculated on the basis of 5 consecutive measurements, and interobserver reliability was calculated using the measurements of the 2 orthopaedic surgeons. The reliabilities between the observers and within each observer were calculated according to the intraobserver, interobserver, and residual variances estimated by the analysis of variance table based on Proc Mixed in SAS software (SAS Institute).

Statistical Analysis

Data were compared between the 2 groups by paired t tests, and analysis of variance and Tukey protected least significant difference test were used for comparisons among >3 areas. Differences were considered significant at $P < .05$.

RESULTS

Participant Demographic Characteristics

The demographic characteristics of the participants are listed in Table 1. There were no significant differences in age, height, or weight between the groups.

Intraobserver Reliability and Interobserver Reproducibility

The intraclass correlation coefficients for intraobserver reliability and interobserver reproducibility were 0.91 (95% CI, 0.84-0.98) and 0.87 (95% CI, 0.80-0.94), respectively. According to the results of a previous study, the intraobserver and interobserver variations during CTOAM analysis were considered acceptable.[8]

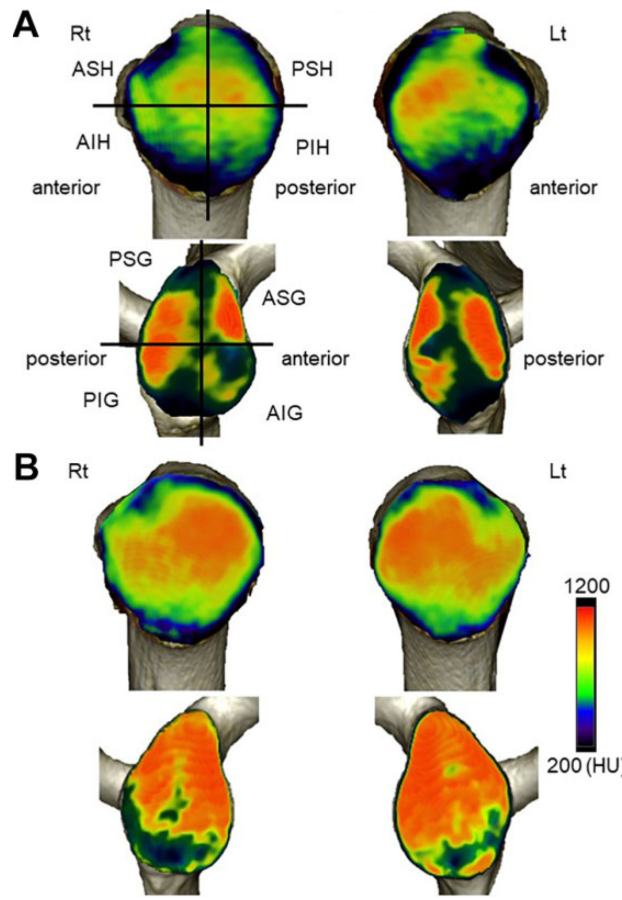

Figure 2. Distribution of subchondral bone density across the articular surfaces of the shoulder joint: (A) control group and (B) gymnast group. AIG, anteroinferior glenoid; AIH, anteroinferior humeral head; ASG, anterosuperior glenoid; ASH, anterosuperior humeral head; HU, Hounsfield unit; Lt, left; PIG, posteroinferior glenoid; PIH, posteroinferior humeral head; PSG, posterosuperior glenoid; PSH, posterosuperior humeral head; Rt, right.

Analysis of the Control Group

In the control group, the mean ± SD bone density of the surface of the humeral head was 541.7 ± 64.6 HU (range, 201-1002 HU) on the dominant side and 531.0 ± 60.4 HU (range, 159-1133 HU) on the nondominant side (Table 2). The mean bone density of the glenoid surface was 875.8 ± 63.1 HU (range, 216-1421 HU) on the dominant side and 854.8 ± 67.8 HU (range, 205-1427 HU) on the nondominant side. No significant difference was seen in the mean density or distribution pattern of the subchondral bone between the dominant and nondominant sides (Table 2, Figure 2A). A bicentric distribution pattern with anterior and posterior maxima was seen in 9 of 10 humeral heads and 9 of 10 glenoids, and monocentric distribution pattern was seen in the remaining humeral head and glenoid (Table 2). On the surface of the humeral head on the dominant side, %HDA was greater in PSH than in ASH ($P = .0044$) and AIH ($P = .0382$) (Figure 3A); on the nondominant side,

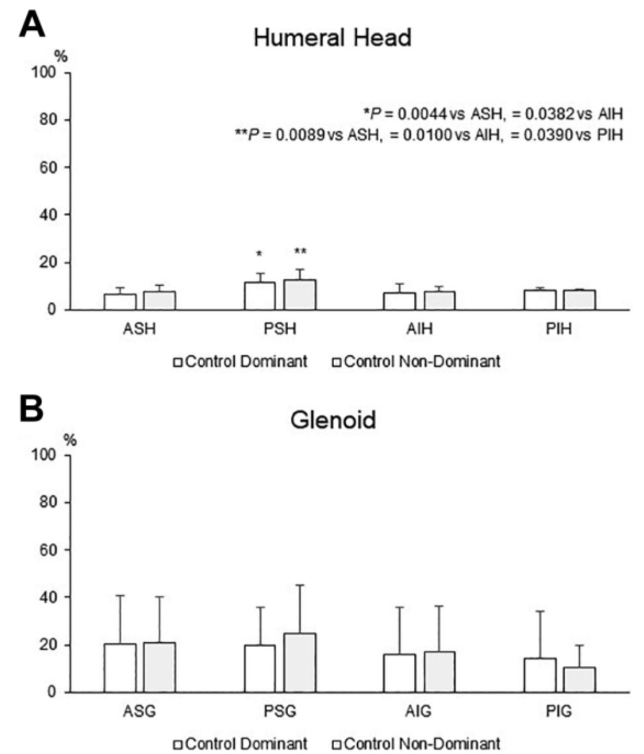

Figure 3. Percentage occupied by high-density area in the control group: (A) surface of the humeral head and (B) glenoid surface. AIG, anteroinferior glenoid; AIH, anteroinferior humeral head; ASG, anterosuperior glenoid; ASH, anterosuperior humeral head; PIG, posteroinferior glenoid; PIH, posteroinferior humeral head; PSG, posterosuperior glenoid; PSH, posterosuperior humeral head.

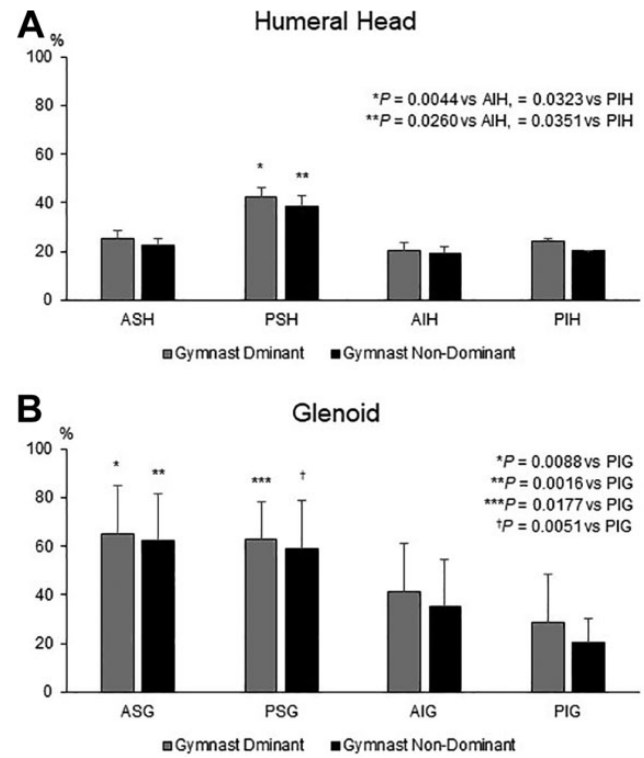

Figure 4. Percentage occupied by high-density area in the gymnast group: (A) surface of the humeral head and (B) glenoid surface. AIG, anteroinferior glenoid; AIH, anteroinferior humeral head; ASG, anterosuperior glenoid; ASH, anterosuperior humeral head; PIG, posteroinferior glenoid; PIH, posteroinferior humeral head; PSG, posterosuperior glenoid; PSH, posterosuperior humeral head.

%HDA was greater in PSH than in ASH (P = .0089), AIH (P = .0100), and PIH (P = .0390). No other significant differences were found among the areas (Figure 3B).

Analysis of the Gymnast Group

In the gymnast group, the mean bone density of the surface of the humeral head was 624.2 ± 49.0 HU (range, 201-1225 HU) on the dominant side and 622.3 ± 63.4 HU (range, 201-1221 HU) on the nondominant side (Table 2). The mean bone density of the glenoid surface was 1027.6 ± 65.7 HU (range, 202-1479 HU) on the dominant side and 1009.1 ± 81.5 HU (range, 202-1461 HU) on the nondominant side. No remarkable change was seen in the mean density or the distribution pattern of the subchondral bone between the dominant and nondominant sides (Table 2, Figure 2B). A bicentric distribution pattern with anterior and posterior maxima was seen in 5 of 12 humeral heads and 5 of 12 glenoids, and a monocentric distribution pattern was seen in 7 of 12 humeral heads and 7 of 12 glenoids (Table 2). On the surface of the humeral head on the dominant side, %HDA was greater in PSH than in AIH (P = .0044) and PIH (P = .0323) (Figure 4A); on the nondominant side, %HDA was greater in PSH than in AIH (P = .0260) and PIH (P = .0351) (Figure 4A). On the glenoid surface on the dominant side, %HDA was greater in ASG (P = .0088) and PSG (P = .0016) than in PIG (Figure 4B); on the nondominant side, %HDA was greater in ASG (P = .0177) and PSG (P = .0051) than in PIG (Figure 4B).

Statistical Comparisons of %HDA Between Groups

The mean bone density of the surface of the humeral head was significantly higher in the gymnast group than in the control group (P = .0028 on the dominant side and P = .0026 on the nondominant side) (Table 2). The mean bone density of the glenoid surface was also significantly higher in the gymnast group than in the control group ($P < .0001$ on the dominant side and P = .0001 on the nondominant side) (Table 2). The distribution pattern of subchondral bone density differed between the gymnast and control groups in that a monocentric pattern was seen in the shoulder in 1 of 10 (10%) controls versus 7 of 12 (58.3%) gymnasts. The %HDA was significantly higher in the gymnast group than in the control group. HDAs were more widely distributed in all shoulders in the gymnast group (in the ASH, PSH, AIH, PIH, ASG, and PSG) than in the control group. On the nondominant side, %HDA values in the ASH, PSH, AIH, PIH,

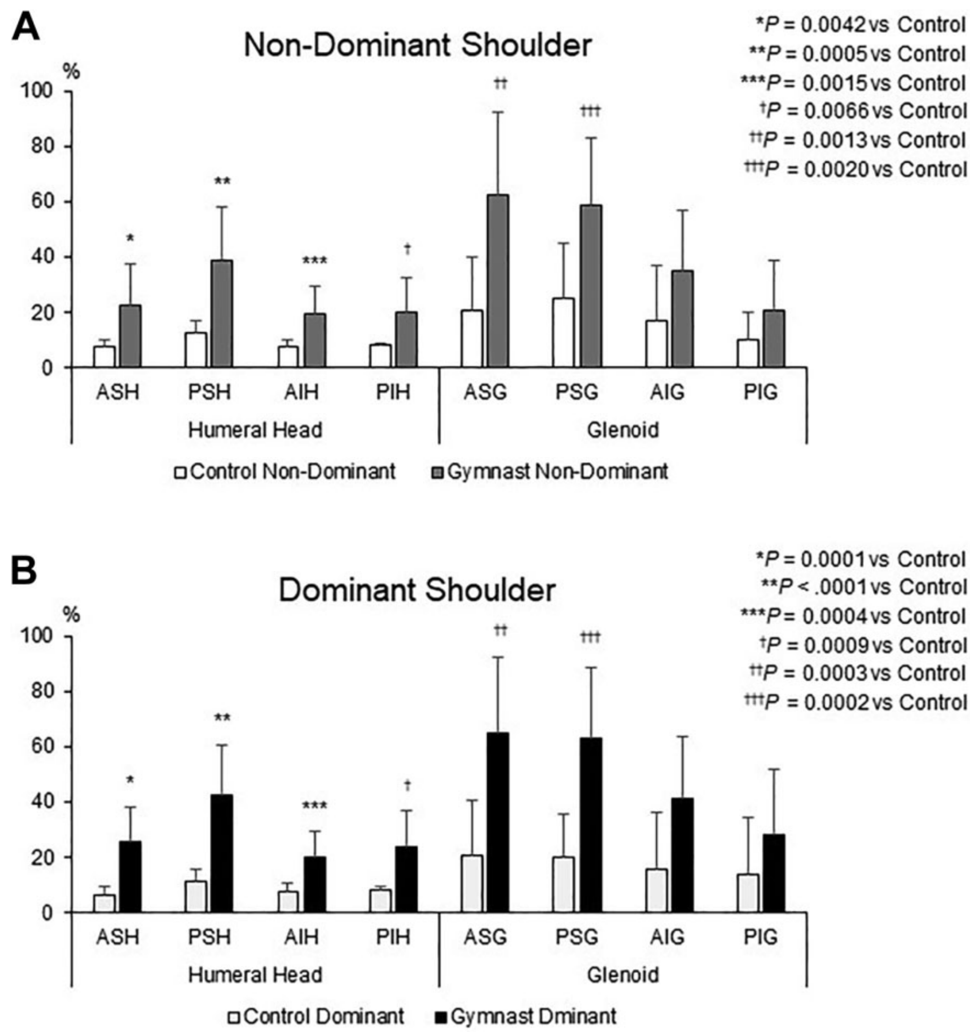

Figure 5. Comparison of percentage occupied by high-density area between the control and gymnast groups: (A) nondominant side and (B) dominant side. AIG, anteroinferior glenoid; AIH, anteroinferior humeral head; ASG, anterosuperior glenoid; ASH, anterosuperior humeral head; PIG, posteroinferior glenoid; PIH, posteroinferior humeral head; PSG, posterosuperior glenoid; PSH, posterosuperior humeral head.

ASG, and PSG were significantly higher in the gymnast group than in the control group (Figure 5A). On the dominant side, %HDA values in the ASH, PSH, AIH, PIH, ASG, and PSG were also significantly higher in the gymnast group than in the control group (Figure 5B).

DISCUSSION

To the best of our knowledge, this is the first evaluation of stress distribution patterns in the shoulder joints of male collegiate gymnasts. The present study demonstrated that stress distribution patterns differed between male collegiate gymnasts and controls. HDAs were detected in the superior articular surfaces of the glenohumeral joint of male collegiate gymnasts, and the mean bone density of the humeral head surface and glenoid surface was higher in the gymnasts than in the controls. The results indicate that in gymnasts, stress is more highly concentrated in the superior part of the glenohumeral joint.

Several cadaveric studies have analyzed the distribution of force through the shoulder joint.[2,3,17] However, it is difficult to simulate the long-term loading conditions of gymnastic activities on the cadaveric joints. Accordingly, we used CTOAM to evaluate changes in stress distribution through the shoulder joint in male collegiate gymnasts, and we successfully clarified the biomechanical characteristics of the articular surfaces of the shoulder under the long-term loading conditions of gymnastic activities. The present study revealed that in the articular joint surfaces of male collegiate gymnasts, HDAs of subchondral bone were located in the PSH and in the anterosuperior and/or posterosuperior articular surface of the glenoid. The basis of CTOAM is that subchondral bone mineralization adapts functionally to repeated and long-term changes in the load on joints.[20] Therefore, the mineralization pattern is an indicator of the mechanical conditions in living joints. Sahara et al[24] reported that the contact area was localized on the posterosuperior part of the humeral head at 135° of abduction. The present results suggest that repetitive gymnastic activities distribute excessive stress through the posterosuperior part of the humeral head and the superior articular surface of the glenoid.

Shoulder injuries are common in gymnastics and are a serious issue for adolescent gymnasts.[5,16,22] Furthermore, 80% of shoulder injuries cause long-term symptoms that may increase the risk of early-onset degenerative disease.[3,31] Chronic repetitive weightbearing by the shoulder predisposes to the degeneration of glenohumeral joint cartilage. Szot et al[28] reported that radiological changes were found in 59.8% of gymnasts' shoulders. Although shoulder pain in gymnasts has been considered a "normal and direct consequence of the sport," the presence of pain in younger athletes must be carefully evaluated.[1] The present results reveal that male collegiate gymnasts experience excessive stress distribution in the superior glenohumeral joint. This may reasonably support the principal role of mechanical conditions in the initiation and/or progression of glenohumeral degenerative disease.

Superior labral injuries are often seen in gymnasts.[10] The mechanism of injury causing such a lesion is unknown but is thought to be secondary to humeral head compression, subtle instability, or a traction injury.[26] Therefore, inhibition of gymnastic activities is advocated for the treatment of early superior labral anterior-posterior (SLAP) lesions.[7,12,27] The current results indicate excessive stress distribution in the superior part of the glenoid in male collegiate gymnasts. This may reasonably support the principal role of mechanical conditions in initiation and/or progression of SLAP lesion and the efficacy of decompression for the lesions by stopping gymnastic activities.

This study has some limitations. First, our analysis was not based on direct measurement of mechanical stress through the shoulder joint. Second, the pattern of stress distribution through living joints is affected mainly by applied loading conditions and joint geometry. Although the present analysis determined the effects of long-term loading conditions generated by gymnastic activities on stress distribution through the shoulder, the influence of joint geometry was not considered. Further studies are necessary to clarify the relationships between the distribution pattern of subchondral bone density and the anatomic parameters of the shoulder joint in gymnasts. Third, the present study was not able to clarify direct relationships between shoulder injury and various predictive factors. The participants in this study had no shoulder symptoms; hence, the changes in the shoulder joint might be normal adaptations. The present study had a small sample size and assessed only male collegiate gymnasts. Fourth, the competition history and period varied among participants. A larger number of participants in a prospective study is necessary to determine the relationship between stress patterns and shoulder injuries.

In conclusion, the present CTOAM analysis indicated that the distribution pattern of mechanical stress through the shoulder in gymnasts is affected by gymnastic activities. In addition, the magnitude of long-term stress acting on the shoulder, especially on the superior glenohumeral joint, was greater in male collegiate gymnasts than in the controls.

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