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. Gymnasts frequently sustain severe injuries such as fractures and dislocations, the majority of which involve the upper extremities. 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.

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. The shoulder can be subjected to forces up to 8.5 times body weight during gymnastic activities. 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. However, few biomechanical studies...
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. Drawing on this theory, Müller-Gerbl et al 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 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.

![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.](image)

| 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).
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. 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 then calculated.
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 postero-inferior humeral head (PIH). The glenoid surface was also divided into 4 parts: anterosuperior glenoid (ASG), posterosuperior glenoid (PSG), anteroinferior glenoid (AIG), and postero-inferior 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

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,
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, 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, PSG, and PIG) than in the control group. On the nondominant side, %HDA values in the ASH, PSH, AIH, PIH,
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. 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 posteroinferior 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. Therefore, the mineralization pattern is an
indicator of the mechanical conditions in living joints. Sahara et al24 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 al24 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.

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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