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**Research article**

# Relationship between maximum shoulder external rotation angle during throwing and physical variables

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**Abstract**
The amount of stress imposed on shoulder and elbow appears to be directly correlated with the degree of maximum shoulder external rotation (MER) during throwing motions. Therefore, identifying risk factors contributing to the increase of MER angle may help to decrease the throwing injuries occurrence in baseball players. The purpose of the present study was to demonstrate the correlation between MER and the kinematic variables at stride foot contact (SFC) during the early cocking phase, the passive range of motion (ROM), and the shoulder strength. The subjects were 40 high school baseball players. Each subject carried out five throwing tasks with his maximum effort. A three-dimensional analysis was performed to obtain the MER, and the shoulder angles of external rotation (ER), extension and abduction at SFC in the early cocking phase. The ROM and muscle strength of the shoulder ER and internal rotation (IR) were also measured. Significant moderate linear correlations were found between the MER and the ER ($r = -0.32$, $p = 0.04$) at SFC, extension angle ( $r= 0.35$, $p = 0.03$) at SFC, IR strength ($r = -0.30$, $p = 0.04$) and passive ROM of ER ($r = 0.46$, $p = 0.01$). The shoulder IR and extension angles at SFC may determine the degree of the MER angle. Furthermore, weak IR muscle strength and excessive ROM of ER might be risk factors for shoulder and elbow injuries. The finding will enable us to establish better prevention and rehabilitation strategies for throwing injuries in baseball players.

**Key words:** Throwing, shoulder, elbow, injury prevention.

## Introduction

It is well accepted that stress imposed on the shoulder and elbow during overhead throwing is a risk factor for throwing injuries in baseball players. Therefore, a number of studies have been directed toward identifying the underlying factor that increases stress on the shoulder and elbow joints (Dillman et al., 1993; Feltner et al., 1986, 1989; Fleisig et al., 1995; 1999; Werner et al., 1993; 2001, 2002; Sabick et al., 2004a; 2004b). Werner et al. (2001) reported that stress imposed on shoulder would increase with the degree of external rotation (ER) during throwing. Sabick et al. (2004b) also stated that the maximum shoulder external rotation (MER) during throwing was the best predictor of the peak elbow valgus stress. These findings indicate that the stress imposed on the shoulder and elbow is directly correlated with the degree of MER. Therefore, excessive MER must be avoided in order to minimize the risk of throwing injuries.

The imposed stress may also be associated with the ratio between the MER and the passive range of motion (ROM) of ER in the throwing shoulder. According to our pilot study, the ratio of MER to passive ROM of ER in the throwing shoulder was significantly greater in baseball players with histories of elbow injuries. This finding suggests that the stress could be magnified by excessive MER itself or the difference in degree between the MER and passive ROM of ER.

Current rehabilitation programs for throwing injuries mainly focus on passive ROM restoration (Wilk et al., 2002). However, scientific evidence indicates that avoiding excessive MER must also be an effective approach for rehabilitation and prevention of the throwing related injuries. Therefore, the purpose of the present study was to investigate the correlations between MER and shoulder strength, passive ROM, and kinematic variables at stride foot contact (SFC) in the early cocking phase during throwing in baseball players. The finding will help us to identify the factors contributing to the increase of MER during throwing.

## Methods

### Subjects

Forty high school baseball players participated in the study. The subjects consisted of 7 pitchers, 2 catchers, 19 infielders and 12 outfielders. The mean (±SD) age, height, body mass and years of baseball experience were 17.0 ± 0.7 years, 1.70 ± 0.06 m, 63.0 ± 10.3 kg and 7.7 ± 2.0 years, respectively. Among the subjects, 37 were right-handed, 3 were left-handed and all used the overhand style. Subjects who experienced any pain or discomfort at shoulder and elbow during the experiment were excluded. A written informed consent signed by each subject was obtained prior to participation in the study. The study protocol was approved by the Ethics Committee of the graduate school of health sciences, Hiroshima University.

### Throwing motion analysis

The MER angle during throwing, and shoulder angles of ER, extension and abduction at SFC in the early cocking phase were measured. Prior to the experiment, reflective markers (diameter, 1.5 cm) were placed at the following bony landmarks of the upper body: dorsal side of the distal end of the humerus; distal end of the throwing forearm (wrist); acromion process; and spinous processes of the 7$^{th}$ cervical (C7) and 8$^{th}$ thoracic (Th8) vertebrae.

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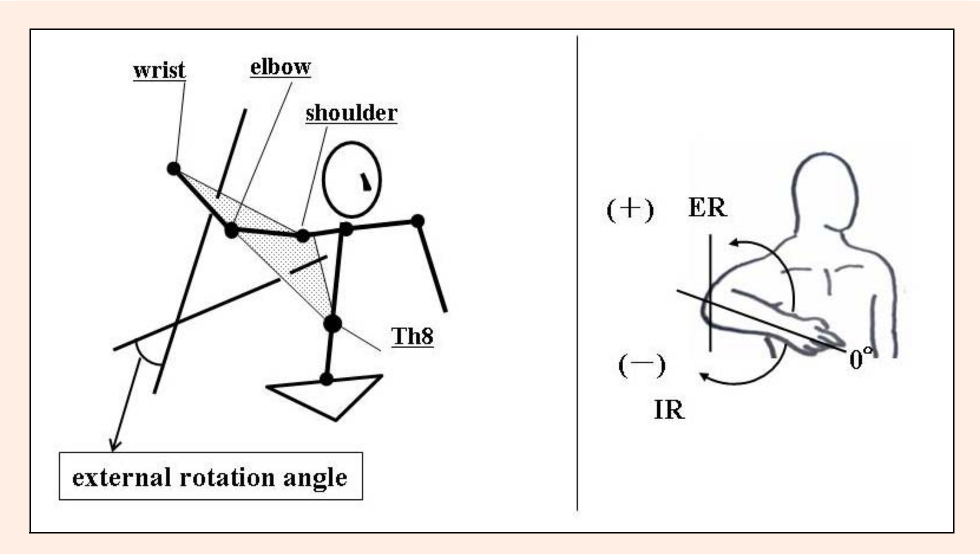


**Figure 1. The definition of the kinematic model for the calculation of shoulder external rotation angle.**

The experimental setting for the data collection was designed to simulate a real baseball practice or game as closely as possible. Specifically, the data collection was performed at an outdoor baseball field, and each subject wore a pair of baseball uniform pants, spiked shoes and a non-sleeved shirt with a hole on the back for the marker placement. The throwing distance was 27.43 m, and the throwing target was a baseball glove held in front of the catcher's chest. Each subject was also asked to wear a glove on their non-throwing hand.

After a regular warm-up, each subject executed five throwing trials toward the target at his maximum effort. The throwing motion was filmed with two high-speed cameras (HSV-400; NAC Image Technology Inc., Tokyo, Japan) and electronically synchronized at 200 frames per second. The positions of the cameras were determined so that the markers were in the field of both cameras during the cocking phase (Sakurai et al., 1993). Therefore, the cameras were located to the right and left rear of the subject. The trial when the thrown ball was most accurately controlled to the target was chosen for further analysis, and then the motion data was transferred to a personal computer (VAIO PCV-LX53/BP; Sony, Tokyo, Japan). The video images were superimposed on the computer display, and the markers were automatically tracked by a 2D-3D motion analyzer (Frame-DIAS II; DKH Inc., Tokyo, Japan). The 3D coordinates of the digitized points in time were obtained using direct linear transformation procedures (Abdel-Aziz et al., 1971).

The definitions of the kinematic models for each shoulder angle calculation are illustrated in Figures 1, 2 and 3. Two corresponding triangles were established between the markers to define the upper body segments for each angle calculation. The corresponding triangles for shoulder ER calculations were formed by the markers on the acromion process, elbow joint and Th8 and those on the wrist, elbow joint and acromion process (Figure 1). The corresponding triangles for shoulder extension angle calculation were formed by the markers on the acromion process, C7 and elbow joint and those on the acromion process, C7 and Th8 (Figure 2). Cosine angles of the inner products calculated with normal unit vectors projected from each corresponding triangle were defined as the shoulder angles (Figures 1, 2). The shoulder abduction angle was defined as the angle between the trunk and the arm lines in the frontal plane (Figure 3). The shoulder angle where the planes (lines in the case of the shoulder abduction calculation) intersected at an angle of 90º was defined as 0°. The ER, flexion and abduction directions were expressed as positive values in this study.

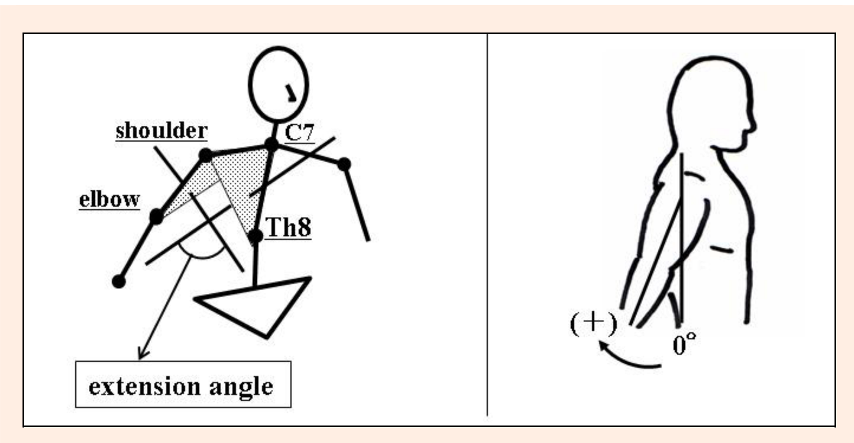


**Figure 2. The definition of the kinematic model for the calculation of shoulder extension angle.**

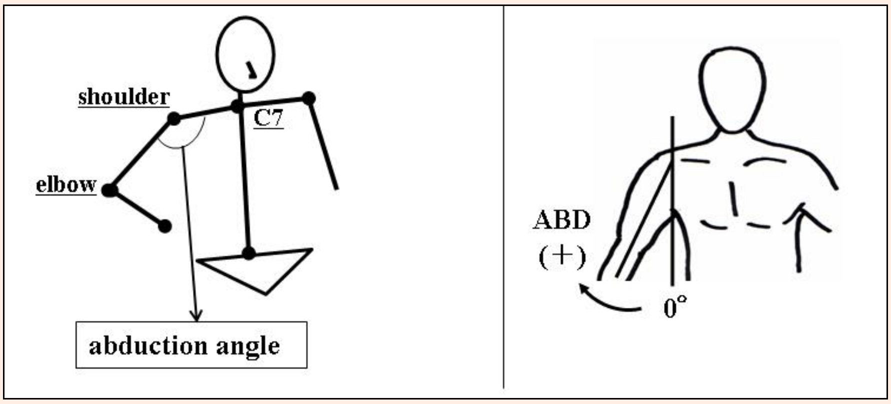


**Figure3.** **The definition of the kinematic model for the calculation of shoulder abduction angle.**

### Passive ROM measurement

The passive ROMs of shoulder ER and internal rotation (IR) were also measured by the 2D-3D motion analyzer. Each subject was placed in the sitting position with the shoulder abduction and elbow flexion angles at 90º. The shoulder was moved passively until the angle reached its maximum position. The passive force applied to the distal end of the forearm during the measurement was maintained at approximately 20 N and confirmed by a handheld dynamometer (Micro FETII; Hoggan Health Industries Inc., Draper, UT, USA). A compensatory lumbar extension movement was not observed during the measurement. After the maximum position was determined by one experienced physical therapist, the shoulder position was captured by a digital video camera. The captured data were then transferred to a personal computer for angle calculation.

### Muscle strength measurement

Isolated maximum muscle strengths of the shoulder ER and IR were measured by manual muscle testing with the handheld dynamometer. The isometric strengths were tested in the sitting position with shoulder angles of 90° abduction, 90° elbow flexion and 90° ER. The examiner stabilized the distal humerus of the subject, and placed the handheld dynamometer on the distal forearm. The examiner used the break test maneuver for strength measurements (Hislop and Montgomery, 1995). The obtained force was converted to a joint moment by multiplying it by the length of the lever arm (distance between the lateral epicondyle of the humerus and the styloid process of the ulna). Finally, the joint moment was normalized by the body weight.

### Statistical analysis

The correlations of the MER with the other three kinematic variables at SFC and the passive ROMs were calculated by the Pearson's rank correlation coefficient. Statistical significance was considered to be indicated at the 5% critical level ($p < 0.05$).

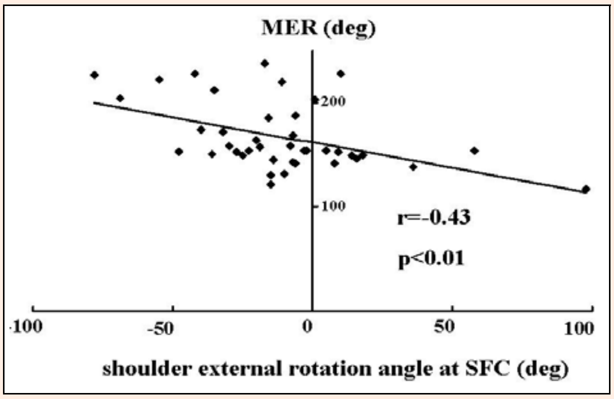


**Figure 4.** **The correlation diagram representing the relationship between maximum external rotation angle during throwing and shoulder external rotation angle at stride foot contact during early cocking phase.**

## Results

Table 1 represents the descriptive data of MER, kinematic variables at SFC, the passive ROM, and the shoulder strength. The mean (±SD) value of the MER was 167±32°. The mean (±SD) values of the shoulder ER and extension angle at SFC during the early cocking phase were -11 ± 32° and 5 ± 14°, respectively. The mean (±SD) ROM of the ER was 118±14°, while that of the IR was 45 ± 14°. The mean (±SD) ER strength was 55 ± 15 Nm/kg, while the mean (±SD) IR strength was 57 ± 16 Nm/kg. Significant correlations were found between the MER and the shoulder ER ($r = -0.43$, $p < 0.01$) (Figure 4) and extension angle ($r = 0.35$, $p = 0.03$) (Figure 5) at SFC. The MER angle was also significantly correlated with the shoulder IR strength ($r = -0.32$, $p = 0.04$) (Figure 6) and the ROM of ER ($r = 0.46$, $p < 0.01$) (Figure 7).

**Table 1.** **Descriptive data of kinematic variables at stride foot contact, passive range of motion (ROM) and shoulder strength. Data are means (SD).**

| | Shoulder angle at stride foot contact (deg) | | | ROM (deg) | | Muscle strength (Nm/kg) | |
|---|---|---|---|---|---|---|---|
| MER (deg) | ER | Extension | ABD | ER | IR | ER | IR |
| 167 (32) | -11 (32) | 5 (14) | 59 (28) | 118 (14) | 45 (14) | 55 (15) | 57 (16) |

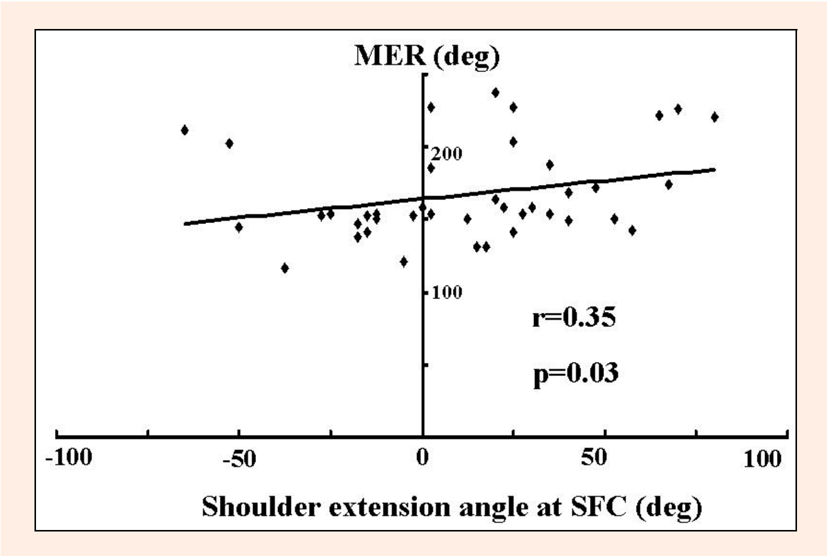


**Figure 5.** **The correlation diagram representing the relationship between maximum external rotation angle during throwing and shoulder extension angle at stride foot contact during early cocking phase.**

## Discussion

Various risk factors for throwing injuries have previously been identified. For example, Olsen et al. (2006) found that the factors most significantly associated with throwing injuries were overuse and fatigue, while Lyman et al. (2001) reported that the risks of shoulder and elbow pain increased with age, body size, fatigue and the number of pitches. Even though it is well accepted that inefficient throwing mechanics increase the stress imposed on the shoulder and elbow joints (Whiteley, 2007), scientific evidences of a relationship between throwing injuries and throwing mechanics have remained inconclusive. Previous studies have demonstrated that the magnitude of shoulder distraction and peak elbow valgus torque are increased according to the degree of MER (Werner et al., 2001; Sabick et al., 2004b). Therefore, identifying the determinant of the degree of MER in throwing mechanics is crucial for both rehabilitation and prevention of throwing injuries.

In the present study, we have demonstrated that the shoulder IR and extension angle at SFC are significantly associated with the MER angle with moderate correlation coefficient, indicating that the imposed stress on the shoulder and elbow may be affected by these kinematic variables. Figure 8 illustrates the typical presentations of proper shoulder mechanics and pathomechanics at SFC that may contribute to the MER increase. Werner et al. (1993) found that pitchers who showed less elbow extension and shoulder abduction angle at SFC encountered less shoulder distraction and valgus stress at the elbow, which supports the current finding. The shoulder IR and extension angles at SFC during the early cocking phase probably play important roles in determining the degree of MER during throwing. From the view of injury prevention, therefore, excessive shoulder IR and extension angles at SFC should be avoided.

Since SFC appears prior to MER occurrence in the kinematic linkage of throwing mechanics, the increase of MER may be occurred as consequences of increased IR

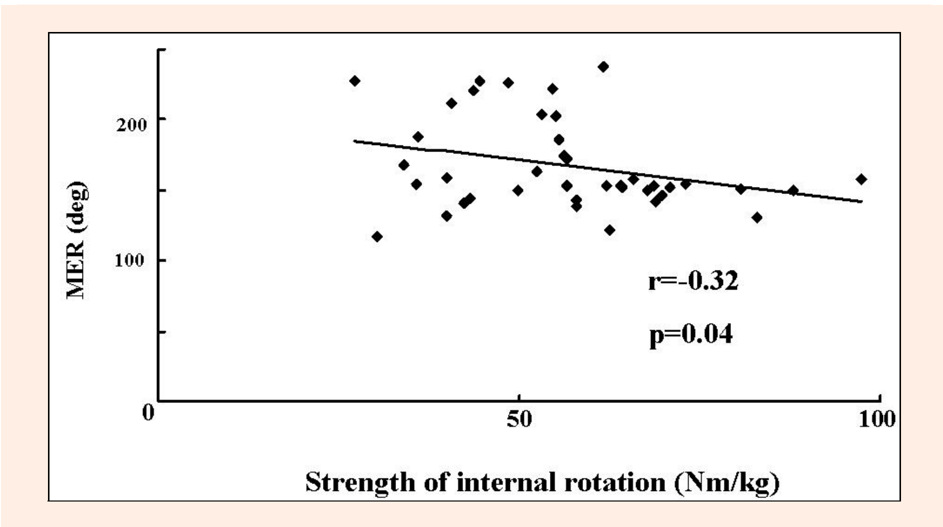


**Figure 6.** **The correlation diagram represents the relationship between maximum external rotation angle during throwing and muscle strength of internal rotation.**

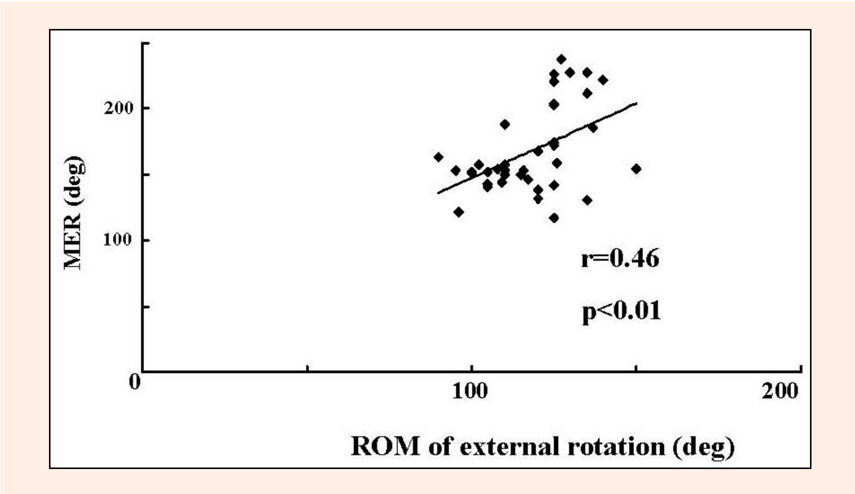


**Figure 7. The correlation diagram representing the relationship between maximum external rotation angle during throwing and range of motion of shoulder external rotation.**

and extension at SFC. However, we should not oversimplify the causal linkage between MER and passive ROM and shoulder strength, and its interpretation warrants careful consideration. Our study has revealed a moderate inverse correlation coefficient between the degree of MER and shoulder IR strength. Shoulder internal rotators function to resist the external rotation torque during the cocking phase. This result suggests that strengthening of the shoulder internal rotators must be incorporated into rehabilitation and prevention programs for throwing injuries. Meanwhile, the throwing mechanics with the increased MER might have been a cause of shoulder IR strength reduction. When MER became greater, the external torque imposed to shoulder internal rotators and adductors would be also greater, which may lead the decrease of the muscular function.

In addition, the passive ROM of shoulder ER was also significantly correlated with the MER angle in the present study. Increased passive ER allows greater MER in shoulder structure; therefore, the degree of passive ER may have contributed to the increase of MER. Meanwhile, previous studies have demonstrated that increased shoulder ER in the throwing arm is attribute to not only soft tissue (Bigliani et al., 1997), but also bony adaptation with a greater retroversion of the humerus (Crockett et al., 2002; Reagan et al., 2002). Therefore, it is also possible that the throwing mechanics with great MER may have induced a structural adaptation to the shoulder and elbow joints, resulting in an increased ROM of shoulder ER.

A relationship between the MER and pitching velocity has also been discussed previously, yet the issue is still a matter of debate. Matsuo et al (2001) demonstrated that the high ball velocity group showed significantly greater MER during throwing than the low ball velocity group. Wang et al. (1995) also suggested that the increase of MER during throwing would increase ball velocity due to a greater linear and angular displacement in the throwing forearm. On the other hand, Stodden et al. (2005) reported that the MER is not significantly associated with ball velocity. Although more evidence is required to

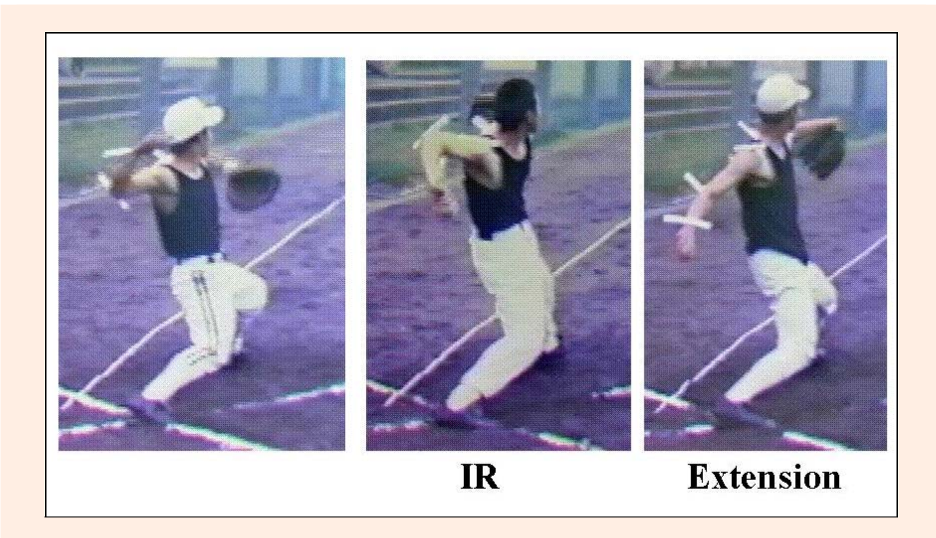


**Figure 8. The typical presentations of throwing mechanics at SFC: The player on the left side demonstrates "proper "shoulder angle at SFC that is frequently seen in non-injured baseball players. When compared to the player on the left side, the player on the center demonstrates greater shoulder internal rotation angle, and the player on the right demonstrates greater shoulder extension angle at SFC.**

clarify the correlation between pitching performance and the MER, controlling MER needs to be considered from the performance perspective as well.

The limitation of our study was that we were not able to conclude whether the increase of MER was a cause or result of the physical and kinematic variables due to the study design. Prospective approach is needed to better understand the causal linkage and the behind mechanism in detail. In addition, since our subjects included not only pitchers but also position players, the more number of pitcher's data must be obtained to allow us to compare with the previous findings.

## Conclusion

The present study has demonstrated the kinematic variables at SFC during the early cocking phase and physical variables are related to the increase of MER during baseball throwing. In the current result, the MER showed significant moderate linear correlations with the ER and extension angles at SFC in the early cocking phase, IR muscle strength and passive ROM of ER. Therefore, avoiding excessive shoulder IR and extension angles at SFC, strengthening IR muscles and maintaining the passive ROM of ER in the normal range may decrease the risk of throwing injuries. Further studies are needed for a more complete understanding of the factors contributing to the increase of MER during throwing.

## References


Abdel-Aziz, Y.I. and Karara, H.M. (1971) Direct linear transformation from computer coordination into object coordinates in close-range photogrammetry. In: *Proceedings American Society of Photogrammetry Symposium on Close-Range Photogrammetry*. Falls Church, VA: American Society of Photogrammetry Symposium on Close-Range Photogrammetry.1-19.

Bigliani, L.U., Codd, P.T., Connor, P.M., Levine, W.N., Littlefield, M.A. and Hershon, S.J (1997) Shoulder motion and laxity in the professional baseball player. *American Journal of Sports Medicine* **25,** 609-613.

Brogdon, B.G. and Crow, N.E. (1960) Little leaguer's elbow. *American Journal of Roentgenology* **83**, 671-675.

Crockett, H.C., Gross, L.B. Wilk, K.E., Schwartz, M.L., Reed, J., O'Mara, J., Reilly, M.T., Dugas, J.R., Meister, K., Lyman, S. and Andrews, J.R. (2002) Osseous adaptation and range of motion at the glenohumeral joint in professional baseball pitchers. *American Journal of Sports Medicine* **30**, 20-26.

Dillman, C.J., Fleisig, G.S. and Andrews, J.R. (1993) Biomechanics of pitching with emphasis upon shoulder kinematics. *Journal of Orthopaedic Sports Physical Therapy* **18**, 402-418.

Feltner, M.E. and Dapena, J. (1986) Dynamics of the shoulder and elbow joints of the throwing arm during a baseball pitch. *International Journal of Sports Biomechanics* **2**, 235-259.

Feltner, M.E. (1989) Three-dimensional interactions in a two-segment kinetic chain. Part II: Application to the throwing arm in baseball pitching. *International Journal of Sports Biomechanics* **5,** 420-450.

Fleisig, G.S., Andrews J.R., Dillman C.J. and Escamilla, R.F. (1995) Kinetics of baseball pitching with implications about injury mechanisms. *American Journal of Sports Medicine* **23,** 223-239.

Fleisig, G.S., Barrentine, S.W., Zheng, N., Escamilla, R.F. and Andrews J.R. (1999) Kinematic and kinetic comparison of baseball pitching among various levels of development. *Journal of Biomechanics* **32**, 1371-1375.

Hislop, H.J. and Montgomery, J. (1995) *Daniels and Worthingham's Muscle testing: techniques of manual examination*. 6th edition. W.B. Saunders Company, Philadelphia, Pennsylvania.

Lyman, S., Fleisig, G.S., Waterbor, J.W., Funkhouser, E.M., Pulley, L., Andrews, J.R., Osinski, E.D. and Roseman, J.M.(2001) Longitudinal study of elbow and shoulder pain in youth baseball pitchers. *Medicine and Science in Sports and Exercise* **33**,1803-1810.

Matsuo, T., Escamilla, R.F., Fleisig, G.S., Barrentine S.W. and Andrew J.R. (2001) Comparison of kinematic and temporal parameters between different pitch velocity groups. *Journal of Applied Biomechanics* **17**, 1-13.

Olsen, S.J., Fleisig, G.S., Dun, S., Loftice, J. and Andrews, J.R. (2006) Risk factors for shoulder and elbow injuries in adolescent baseball pitchers. *American Journal of Sports Medicine* **34**, 905-912.

Reagan, K.M., Meister, K., Horodyski, M.B., Werner, D.W., Carruthers, C. and Wilk, K. (2002) Humeral retroversion and its relationship to glenohumeral rotation in the shoulder of college baseball player. *American Journal of Sports Medicine* **30**, 354-360.

Sabick, M.B., Torry, M.R., Kim, Y.K. and Hawkins, R.J. (2004a) Humeral torque in professional baseball pitchers. *American Journal of Sports Medicine* **32**, 892-898.

Sabick, M.B., Torry, M.R., Lawton, R.L. and Hawkins, R.J. (2004b) Valgus torque in youth baseball pitchers. A biomechanical study. *Journal of Shoulder and Elbow Surgery* **13**,349-355.

Sakurai, S., Ikegami, Y., Okamoto, A., Yabe, K. and Toyoshima, S. (1993) A three-dimensional cinematographic analysis of upper limb movement during fastball and curveball baseball pitches. *Journal of Applied Biomechanics* **9**, 47-65.

Stodden, D.F., Fleisig, G.S., McLean, S.P. and Andrews, J.R. (2005) Relationship of biomechanical factors to baseball pitching velocity: within pitching variation. *Journal of Applied Biomechanics* **21**, 45-56

Wang, Y.T., Forf, H.T. 3rd, Ford H.T. Jr, and Shin D.M. (1995) Three-dimensional kinematic analysis of baseball pitching in acceleration phase. *Percept Mot Skills* **80**,43-48.

Werner, S.L., Fleisig, G.S., Dillman, C.J., and Andrews, J.R. (1993) Biomechanics of the elbow during baseball pitching. *Journal of Orthopaedic Sports Physical Therapy* **17**, 274-278.

Werner, S.L., Gill T.J., Murray, T.A., Cook, T.D. and Hawkins R.J. (2001). Relationships between throwing mechanics and shoulder distraction in professional baseball pitchers. *American Journal of Sports Medicine* **29**, 354-358.

Werner, S.L., Murray, T.A., Hawkins, R.J., and Gill, T.J. (2002). Relationship between throwing mechanics and elbow valgus in professional baseball pitchers. *Journal of Shoulder and Elbow Surgery* **11**,151-155.

Whiteley, R. (2007) Baseball throwing mechanics as they relate to pathology and performance-A review. *Journal of Sports Science and Medicine* **6**, 1-20.

Wilk, K.E., Meister K. and Andrews, J.R. (2002) Current concepts in the rehabilitation of the overhead throwing athlete. *American Journal of Sports Medicine* **30**,136-151.


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## Key points

- It has been reported that the amount of stress imposed on shoulder and elbow joints is correlated with the degree of maximum shoulder external rotation angle (MER) during throwing. Therefore, controlling MER within a normal range plays a key role in the prevention for throwing-related injuries in baseball players.
- Physical and biomechanical factors related to the degree of MER must be addressed to advance the current prevention and rehabilitation strategies for the shoulder and elbow injuries.
- The current finding demonstrated that there was a significant moderate leaner correlation between shoulder internal rotation angle at the initial foot contact in the early cocking phase and MER.
- Passive ROM of shoulder external rotation was also associated with the degree of MER. However, the passive ROM could be a consequence of excessive MER during throwing.

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## APPENDIX

### Equations for shoulder external rotation angle calculation

Points (x1, y1z1), (x2, y2, z2), (x3, y3, z3), and (x4, y4, z4) represent marker positions of acromion, elbow, wrist, and Th8, respectively, in the 3D coordinate system. Inner product A(X1, Y1, Z1) was projected perpendicularly from established triangle between acromion, elbow, and Th8 markers.

Vector A (X1,Y1, Z1) was calculated by the equations below:

$$X1 = (y2-y1)*(z3-z1)-(y3-y1)*(z2-z1)$$
$$Y1 = (z2-z1)*(x3-x1)-(z3-z1)*(x2-x1)$$
$$Z1 = (x2-x1)*(y3-y1)-(x3-x1)*(y2-y1)$$

Inner product B (X2, Y2, Z2) was calculated with acromion, elbow, and Th8 markers by the equations below:

$$X2 = (y2-y1)*(z4-z1)-(y4-y1)*(z2-z1)$$
$$Y2 = (z2-z1)*(x4-x1)-(z4-z1)*(x2-x1)$$
$$Z2 = (x2-x1)*(y4-y1)-(x4-x1)*(y2-y1)$$

Shoulder external rotation was defined as the inner product between the two vectors:

$$\cos\theta=(X1*X2+Y1*Y2+Z1*Z2)/(\sqrt{(X1*X1+Y1*Y1+Z1*Z1)} * \sqrt{(X2*X2+Y2*Y2+Z2*Z2)})$$

The angle between two vectors (A,B) was obtained by calculating acosθ, which was defined as shoulder external rotation angle in this study.