INTRODUCTION

Recently, the relationships between shoulder abduction angle at ball release during baseball pitching and several throwing arm kinetics were investigated by means of computer simulation (Matsuo, et al., 2002). The results showed that the shoulder abduction for the professional baseball pitcher was consistent with the angle where the sum of the time-integrated torque-squared or the time-integrated torque change of the throwing shoulder and the throwing elbow, during the delivery, was minimized. It suggested that the throwing arm movement for well-trained pitchers might be regulated based on some minimum principle observed in some other movements such as reaching (Alexander, 1997), walking, running (Cavanagh & Williams, 1982), or slalom-like ski movement (Almåsbakk, et al., 2001). We regarded the angle showing such minimum torque-squared as an optimal angle during pitching, in the current study.

The optimal shoulder abduction was different among the participants in the previous study (Matsuo, et al., 2002). In the extreme cases, those for underhand pitchers were approximately 70° or 80° and those for overhand pitchers were often over 120°. For most subjects, observed and optimal shoulder abduction were similar. On the other hand, it has been stated that shoulder abduction less than 90° during arm acceleration phase may induce elbow injuries (Norwood, et al., 1978) and that 90° of shoulder abduction has an advantage in stabilizing humerus in the glenoid fossa (Poppen & Walker, 1978). It is not reasonable to make the throwing shoulder abduct at 90°, without correspondence with minimum torque-squared or some other minimum criterion, because to do so may require excessive of effort. It is desirable that the optimal shoulder abduction angle defined in this study is 90° or a little higher.

If throwing arm movement is regulated based on some minimum principle, the trunk movement may influence the optimal shoulder abduction angle. Therefore, it is valuable to investigate the relationship between trunk movement and optimal shoulder abduction angle. In this study, we focused on the lateral tilt of the trunk movement. Thus, the purpose of this study was to investigate change in optimal shoulder abduction angle (in terms of the minimal torque-squared), as a function of lateral trunk tilt.

METHODS

Motion data of seven professional baseball pitchers (height 1.86 ± 0.04m, mass 89.8 ± 10.4kg, age 24.4 ± 3.3yrs, ball speed 38.0 ± 1.3m/s) were collected, using four 200Hz infrared cameras (Motion Analysis, Santa Rosa, CA), at the American Sports Medicine Institute. Reflective markers (38.1 mm diameter) were attached bilaterally at the lateral malleoli, lateral femoral epicondyles, greater trochanters, lateral superior tip of the acromions, and lateral humeral epicondyles. A reflective marker was also attached at the ulnar styloid process of the non-throwing wrist, while a reflective band was placed around the throwing wrist. The locations of those reflective passive markers and band were calculated with an automatic digitizing system, utilizing the direct linear transformation method. The root mean square error in the calculation of the three-dimensional marker location with a calibration matrix approximately 1.5m X 1.2 m X 1.2 m in size was found to be less than 10 mm. The motion data from 0.1s before lead foot contact to 0.1s after ball release were used in the following analyses.

From the locations of surface markers, the center of each joint was estimated (Fleisig, et al., 1996). Then, several local coordinates and joint angular parameters were calculated. For a trunk coordinate ($R_t$ in Figure 1), $Z_t$ was defined as a vector of the longitudinal axis for the upper arm ($Z_t$) and the inferior unit vector of the trunk (-$Y_t$); that is, a posture in which the arm is hung vertically was 0° and a posture in which the elbow was level with the shoulder was 90° of abduction. For the pelvis coordinate, $Z_p$ was defined as a unit vector from non-throwing shoulder to the throwing shoulder, $X_p$ was defined as a unit vector of the cross product of the trunk vector from mid-hip to mid-shoulder and $Z_p$, and $Y_p$ was the cross product of $Z_p$ and $X_p$. The shoulder abduction angle was defined as the angle between a unit vector of the longitudinal axis for the upper arm ($Z_t$) and the inferior unit vector of the trunk (-$Y_t$); that is, a posture in which the arm is hung vertically was 0° and a posture in which the elbow was level with the shoulder was 90° of abduction. For the pelvis coordinate, $Z_p$ was defined as a unit vector from left hip to right hip, $X_p$ was defined as a unit vector of the cross product of $Y_t$ and $Z_p$, $Y_p$ was defined as a unit vector of the cross product of $Z_p$ and $X_p$. The lateral trunk tilt angle was defined as the angle between the unit vector of the trunk ($Y_t$) and the vertical axis of the pelvis coordinate ($Y_p$). This definition may have an inherent problem for using as the lateral trunk tilt angle when it is compared among subjects. It is, however, reasonable to use it in the current study, because the angle was used as a comparison within each subject.

Direct kinematics using the matrix transformation was used to calculate joints positions for the simulated motions. By rotating $X_t$ and $X_p$ for the actual pitching motion, the simulated motions with various lateral trunk tilt angles and various shoulder abduction angles were generated.
Q = EP  
\[ Q = \begin{bmatrix} Q_x, Q_y, Q_z \end{bmatrix}^T \]

\[ E = \begin{bmatrix}
C + n_z^2(1-C) & n_z S + n_y n_x (1-C) & n_y S + n_z n_x (1-C) \\
-n_z S + n_y n_x (1-C) & C + n_z^2(1-C) & -n_y S + n_z n_x (1-C) \\
n_z S + n_y n_x (1-C) & -n_y S + n_z n_x (1-C) & C + n_z^2(1-C)
\end{bmatrix} \]

where \( C \) and \( S \) mean the cosine and the sine functions of the angle manipulated, respectively. \( nx, ny, \) and \( nz \) mean the projected length of the unit vector for the rotational axis to the global coordinate.

The target angles at the instant of ball release for the lateral trunk tilt were -20, -10, 0, 10, 20, 30, 40° (0° means \( Y_t = Y_p \) and negatives mean ipsilateral bending) and those for the shoulder abduction angles were 70, 80, 90, 100, 110, 120°. Forty-two \((7 \times 6)\) motions were, therefore, generated for each subject (Figure 2). Although these parameters were changed, all angular velocities remained the same as the actual motions.

\[ F_{f_d} = -m a_t \]
\[ F_{f_p} = m a_t - m g - F_{f_d} \]

\[ \tau_{f_p} = I_{f_t} \omega_{f_t} - r_{f_d} \times F_{f_d} - r_{f_p} \times F_{f_p} \]

\[ \tau_{u_p} = I_{u_l} \omega_{u_l} + I_{u_t} \omega_{u_t} + r_{u_d} \times F_{f_p} - r_{u_p} \times F_{u_p} + \tau_{f_p} \]

where \( F = \) force, \( \tau = \) torque. Subscripts h, f, and u represent hand, forearm, and upper arm, respectively. Subscripts d, p, l, and t represent distal joint, proximal joint, longitudinal axis, and transverse axis, respectively. \( I, \omega, \) and \( x \) are the moment of inertia, the first derivative of angular velocity, and the cross product, respectively. The resultant forces and torques of the elbow joint and the shoulder joint calculated above were transformed into \( R_f \) coordinates and \( R_t \) coordinates, respectively. The squared values of both the resultant shoulder torque and the elbow torque were calculated and integrated over time:

\[ \Sigma(\tau_{f_p}^2 + \tau_{u_p}^2) \]

where \( \tau_{f_p} \) is the torque for the throwing elbow and \( \tau_{u_p} \) the torque for the throwing shoulder. The torque-squared for each simulated motion was normalized to the actual motion. Therefore, the torque-squared observed in the actual was 1.0.

RESULTS

Figure 3 illustrated that the lateral trunk tilt during pitching influenced the optimal shoulder abduction angle. The optimal shoulder abduction angle in each condition, defined as the angle where the normalized torque-squared in each line was the minimum, was different among conditions in the same subject. In the contra-lateral trunk tilt (from 10° to 40° conditions), the optimal shoulder abduction ranged from 90° to 105°. While, in the ipsi-lateral (-10° and -20°) conditions, the torque-squared decreased as shoulder abduction increased. The optimal shoulder abduction in the ipsi-lateral conditions was not found in the range between 70° and 120°. Generally, the ipsi-lateral trunk tilt required greater torque-squared than the contra-lateral trunk tilt did. Shoulder abduction less than 90° required greater torque-squared than 90° of shoulder abduction.

The relationship between torque-squared and the combination of the shoulder abduction and lateral trunk tilt is shown as contour patterns in Figure 4. The minimal torque-squared was found with the combination of 100° of the shoulder abduction and 30° of the lateral trunk tilt (a dark green triangle in the right bottom panel in Figure 4). The minimum torque-squared ranged from 0.90 for FC to 0.99 for BW and JM. The mean was 0.95 ± 0.03.

The fact that the ellipses lean to the left means that the optimal shoulder abduction increased as the lateral trunk decreased. From the individual perspective, individual differences were observed in the optimal combination and the shape and the density of the contours.
Figure 3: Two examples of the time-integrated torque-squared of the throwing arm. The values were normalized with that of the actual motion. Each line represents a different condition of lateral trunk tilt.

Figure 4: Relationship between normalized torque-squared and the combination of shoulder abduction angle and lateral trunk tilt. The contour lines represent the normalized torque-squared. Blue arrows show the actual data, red triangles show the minimum values in the simulated conditions, a light green arrow shows the mean of the actual data, and a dark green triangle shows the minimum of the mean of the simulated conditions.

DISCUSSION

In the previous study investigating the effect of shoulder abduction angle on throwing arm kinetics (Matsuo et al., 2002), the mean values of the optimal shoulder angles for overhand and three-quarter hand pitchers were $107^\circ \pm 14^\circ$, $104^\circ \pm 14^\circ$, respectively. It was also reported that the optimal shoulder abduction for two underhand pitchers were $68^\circ$ and $79^\circ$. From these results, we expected that the lateral trunk tilt affected the optimal shoulder abduction angle with some positive relationship. However, the results of this study showed that lateral trunk tilt affected optimal shoulder abduction angle with rather negative relationship. One possible reason for this discrepancy is that lateral trunk tilt angle is only one kinematic factor, but there may be some other critical factors. Matsuo et al. (2000) reported kinematic and kinetic characteristics of sidearm and underhand pitching. The kinematic differences from the overhand and three-quarter pitching were found in not only the shoulder abduction angle and the lateral trunk tilt angle, but also the elbow extension angular velocity. It may have affected the results. The movement of the throwing shoulder may be the other kinematic factor. Escamilla et al. (2002) and Matsuo et al. (2001) compared kinematic and kinetic parameters between two groups with different ball velocity. They found several kinematic and kinetic differences and indicated that forward trunk tilt played a crucial role to throw the fastball faster. The previous study (Matsuo, et al., 2002) used Japanese professional baseball pitchers whose average ball velocity was 36 m/s, whereas the average ball velocity was 38 m/s in the current study. The similar difference of forward trunk tilt may have affected the results.

Figure 4 indicates the importance of focusing on individuals. The shape or the density of the contours, indicating the degree of the effect of the angle change, was different among the participants. The greater diameter or the gentle density means the effect of the angle change is less, or vice versa. Although the actual data for subjects LH and HF deviated from the mean optimal combination (the shoulder abduction = $105^\circ$, the lateral trunk tilt = $30^\circ$), changing their movements to the mean optimal combination requires greater torque. The course of developing the combination or the coordination of the movement depends on the optimal combination as well as the actual combination.

Most previous studies on baseball pitching have focused on elite (professional and college) baseball pitchers. The mean data for those elite athletes may not represent all pitchers, nor should be always followed as a good example. Further investigations using computer simulation approach may be helpful.

REFERENCES