

Coordination of Elbow, Shoulder, and Trunk Movements in the Backswing Phase of Baseball Pitching to Throw a Fastball

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ABSTRACT

Background: Baseball pitchers adopt a backswing motion to accelerate a forward swing of the arm and project the ball. However, knowledge about the backswing movement for delivering a fast pitch has not been accumulated enough. **Objective:** This study aimed to identify the kinematic parameters of the backswing movement associated with differences in the speed of pitches and capture the joint kinematics of the throwing arm in the backswing phase. **Methodology:** Based on the quasi-experimental study design, fifteen male college students with various levels of baseball experience pitched a baseball at their maximum, 40%, 60%, and 80% of their full ball speed. A motion capture system sampled data at 250 Hz, and three-dimensional data were acquired for shoulder and elbow joint movements, upper-trunk rotation, and ball movement in the backswing phase. Correlation analysis between the joint and ball parameters was conducted, and the relative timings of these parameters were calculated. **Results:** The speed of pitch showed a significant correlation with the ball peak speed in the backswing phase ($r = 0.75$), which showed a significant correlation with the velocity of the elbow flexion ($r = -0.81$), shoulder abduction ($r = 0.75$), external rotation ($r = -0.86$) and the upper trunk's rotation ($r = 0.75$). **Conclusions:** The backswing movement producing the higher ball's peak speed and its abrupt transition to the forward swing was associated with the higher release speed. This kinematic feature was achieved by the temporal coordination of the arm joint movements with the upper trunk's rotation.

Key words: Applied Kinesiology, Task Performance, and Analysis, Biomechanical Phenomena, Upper Extremity, Baseball

INTRODUCTION

Delivery of a ball as fast as possible in baseball pitching is achieved by integrating movements of whole-body segments consisting of multiple motion phases (Figure 1). A forward arm swing for projecting a ball is preceded by a backswing motion, which is accompanied by stepping a leading foot in the direction of pitch, transferring the body's center of gravity toward the direction of a pitch, and rotating the trunk (Calabrese, 2013).

Kinematic and kinetic analysis of joint movements of a throwing arm have been conducted (e.g., Escamilla, Fleisig, Zheng, Barrentine, & Andrews, 2001; Feltner, 1989; Feltner & Dapena, 1986; Hay, 1993; Matsuo, Matsumoto, Mochizuki, Takada, & Saito, 2002; Stodden, Fleisig, McLean, & Andrews, 2005), and those studies have shed light on the pattern of movements of the joints of the throwing limb and how the torque of those joints work to rotate the joints. However, many of those studies focused primarily on kinematics/kinetics in the movement phase of a forward arm swing, even though the backswing motion phase is also important since pitchers adopt a backswing movement

as a counter-movement aiming to enhance the acceleration of the forward arm swing. In the practical field of playing and coaching baseball, knowledge about the association of the backswing movement regarding the production of high-speed pitches is vital to facilitate the improvement of pitching movements (e.g., House, Heil, & Johnson, 2006; Johnson, 2013). Knowledge about how to move for a backswing movement for producing a forward arm swing effectively to pitch a ball will contribute to developing a method of coaching and practicing pitching movements. However, a study from this viewpoint has not been conducted yet. Relevant to this issue, there was a previous study by Katsumata, Sasaki, and Kawai (2017), which investigated the backswing movement of ten high-school baseball pitchers by correlation analysis among kinematic parameters of the ball and joint movements. Although the study by Katsumata et al. (2017) provided interesting clues regarding the movement parameters that are associated with achieving a higher speed of the pitch, it should be noted that correlation analysis does not determine a cause and effect relationship between parameters. In addition, correlation results themselves do not reveal

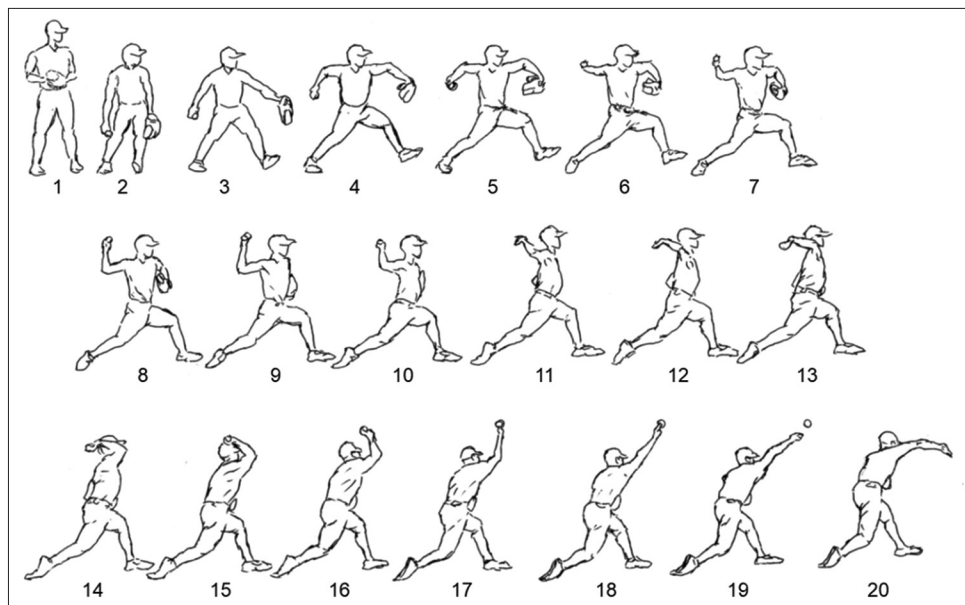


Figure 1. A pitching movement is composed of the following movement components: A backswing arm motion (2 to 13), a stepping movement of a leading foot toward the pitching direction (2 to 7), a trunk rotation (6 to 17), and a forward arm swing (13 to 20).

temporal relationships between the parameters. Therefore, more findings in addition to their study (Katsumata et al., 2017) need to be accumulated to argue for the contribution of backswing movements for the higher speed of pitches. Even though the correlation analysis conducted by Katsumata et al. (2017) may not be sufficient to argue for the mechanical cause and effect of the backswing movement, their focus on ball kinematics in association with the kinematic parameters of backswing movement is interesting from the viewpoint of the study of motor control and learning, which was proposed by Bernstein (1967) and the body of knowledge has been built (Andel et al., 2021; Kugler & Turvey, 2015; Latash, 2010 2020; Newell & Liu, 2021; Pacheco, Lafe, & Newell, 2019). According to this viewpoint, a multi-joint movement must be organized to produce a movement of an end-point effector (i.e., a hand gripping a ball), which is directly related to achieving a performance goal (i.e., delivering a fastpitch), and therefore the analysis of the end-point effector movement can provide us an insight of how a whole-body movement is produced to achieve a goal of the movement. The authors of the present study apply this idea to pitching movements and assume that the multiple body segments available are exploited to produce the ball movement for delivering a high-speed pitch. Therefore, the authors expect that the analysis of the ball kinematics will provide information regarding the characteristics of backswing movement.

Based on the above perspective, the authors of the present study approach the backswing movement in baseball pitching by attempting to identify kinematic parameters of the backswing movement, which are associated with the speed of pitches. In addition to correlation analysis to determine the kinematic relationship between movement parameters, another important analytical viewpoint is the temporal coordination of movement components composing a backswing. Arm segments' movements need to be temporally coordinated to orga-

nize a pitch to be as efficient mechanically as possible in order to produce the highest possible pitch speed since a backswing arm movement is composed of multiple joint movements by shoulder and elbow joints. These movement components are produced with the rotation of an upper trunk. Therefore, the meaning of correlation results about movement parameters, which are identified as candidates for critical parameters of the backswing movement, can be interpreted by focusing on the relative timing of these movement components. And thereby, those implications obtained by the results of the vital backswing movement parameters provide hints to explore the effective backswing movement in practicing pitching movements.

For identifying kinematic parameters associated with the speed of the pitch, the present study examines pitchers' backswing movements, whose performance levels are different in terms of the rate of pitches. Given the wide range of pitch speeds, it was expected that the correlation analysis reveals kinematic parameters of the ball that capture the features of a backswing movement, which is associated with the high-speed pitch. Once the key ball parameters were obtained, correlation analysis between those parameters and joint kinematics of the throwing arm was conducted, and the meaning of correlation results is discussed, taking into consideration the temporal relationship, which was shown by the relative timing of the joint kinematics and the key ball parameters. Finally, the implications of the pattern of backswing movement for producing the pitch's speed are discussed.

METHODOLOGY

Participants and Study Design

The study design was quasi-experimental such that participants who have experience of playing baseball at different performance levels pitched a ball at different speeds, and the ball and arm movement kinematics were analyzed. To

this end, fifteen male college students (mean age 21.6 ± 0.8 years) participated in the study. The sample size (n) is calculated as below (Daniel & Cross, 2013).

$$n = [z^2 * p * (1 - p)/e^2] / [1 + (z^2 * p * (1 - p)/(e^2 * N))]$$

Where z is the z -score for a confidence level of 90%, p is population proportion; N is the population size, and e is the margin of error. When those parameter values were assumed to be $z = 1.645$, $p = 0.5$, $N = 10000$, and $e = 0.2$, the sample size was equal to 17. And when the margin of error was assumed to be 0.25, the sample size was equal to 11. Based on those results, this study used fifteen as the sample size. All participants were right-handed, and the mean and standard deviation of their height and weight were 1.75 ± 0.05 m and 72.1 ± 8.7 kg, respectively. The participants pitched the ball with an over-handed style using their own comfortable and preferred style. The relationship between the pitch speed and the characteristic of movements of the pitching arm across different levels of pitching performance in terms of their speed of pitches was examined. To this end, students who took a softball class of the university and had different levels of baseball experience were selected as candidates of the participant, among which fifteen students were interested in participating in the experiment. Five participants were recreational players; three played in a baseball club in their high-school days, and seven were college baseball players. Those students' maximum pitch speed was checked by a pilot test using a radar gun. Given these diversified levels of pitching performances, their pitch velocity at their maximum effort ranged from 19.2 m/s to 34.9 m/s. For the analysis, the dependent variables were the ball kinematic parameters of the forward swing phase. The independent variables were the ball kinematic parameters and the kinematics of elbow and shoulder joint rotations in the backswing phase. After the purpose and procedure of the experiment were explained, the participants signed an informed consent form. This study was conducted using the principles prescribed in the Helsinki Declaration, and it was approved by the appropriate ethics committee (KSH14-018).

Procedure

An experimental setup, whose protocol was based on the previous study (Katsumata et al., 2017), is described in Figure 2.

The participants delivered the ball to the target. Their movements and ball trajectories were recorded by a motion capture system with eight high-speed cameras by optical marker-based technology (Vicon MX, Oxford Metrics, U.S.A.) at 250 Hz. Reflective markers were stuck on the ten anatomical landmarks to record each participant's upper limb and trunk movements: the right and left acromion (shoulders) and iliac crest (hips), the right and left limb olecranon (elbow), the right and left ulnar styloid process (wrist), and the right and left proximal parts of the third digit proximal phalange (hand). To record the movement of a baseball, the reflective tape was stuck on the ball surface.

Test Procedure

In the pitching performance, participants were asked to take the stretch position (Figure 1-1) and initiate their pitching

actions. The participants pitched along with two task conditions. In the first task condition, they pitched the ball to the target as fast as possible (the maximum speed), and repeated it eight times. In the second task, participants threw the ball at 40%, 60%, and 80% of the mean value of the maximum speed condition, with eight trials for each of these speed conditions. In this submaximal speed condition, the trial was repeated until the speed criterion was achieved when the pitch speed was one standard deviation away from the mean maximum speed. The sequence of these 24 trials was the ascending-descending order or the descending-ascending order, by repeating four trials for each target speed before moving to the next target speed. The participants were assigned to one of the above two trial sequences for counter-balancing the effect of trial order across the participants.

Data Acquisitions

The three-dimensional positions of the ball and the reflective markers were obtained via a motion capture system (Vicon Workstation, Vicon Peak, U.S.A.). A global coordinate system was defined, as described in Figure 2. For smoothing the position data of the markers and ball, a second-order low-pass filter was used with a cutoff frequency of 20-Hz. The velocities of the ball and marker movements were calculated using numerical differentiation.

To capture the ball movement, the time derivative of the position vectors of the ball (the ball speed) was calculated as below.

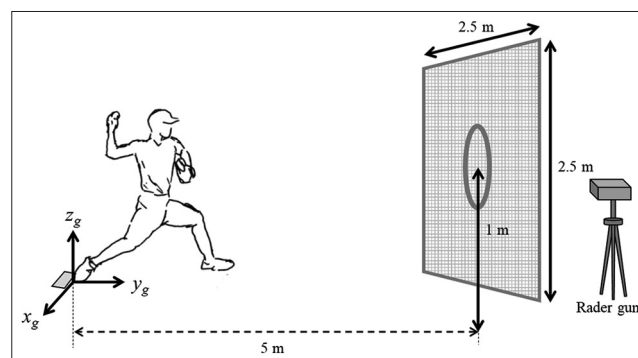


Figure 2. A net (2.5m high and 2.5 m width) was placed 5 m away from a pitcher's plate, and a circular target with a diameter of 0.7 m was shown on the net at the 1 m height from the ground. A radar gun was placed behind the net at the height of the target's center to measure the pitch's velocity. Given a set of the target's size and distance, the accuracy demand of the throwing task was not challenging to enable the participants to focus on producing their maximum effort for the pitch at speed as fast as possible. The origin of the global reference frame was defined at the midpoint of the front edge of a pitching rubber, where the participants set their right foot to take the stretch position, and its axes are shown in the figure: y_g was horizontal in the direction of the pitching; z_g was vertical, and x_g was perpendicular to x_g and y_g and parallel to the pitching rubber.

$$\text{Ball speed} = \frac{\sqrt{(x_{n+1} - x_n)^2 + (y_{n+1} - y_n)^2 + (z_{n+1} - z_n)^2}}{\Delta t}$$

Where x , y , and z refer to the coordinates of the ball's position in the global reference frame; n refers to the number of the sampling frame, and $n+1$ is the frame after the n th frame. Δt refers to the sampling period of 4 ms.

An exemplary profile of the ball speed and its acceleration (Figure 3) revealed the onset of the ball speed increase (*BSW*) to its peak value followed by the decrease of it before the start of the abrupt increase of the speed (*FWD*).

For analysis, the following ball kinematic parameters were obtained: the maximum value of the ball speed (V_{peak}) and the minimum value of its negative acceleration (A_{min}) prior to *FWD* in the backswing phase, and the maximum acceleration of the ball (A_{max}) in the forward swing phase. The release velocity of the ball ($V_{release}$) was obtained by calculating the slope of linear regression, conducted for five data points of the y -component (the direction of pitch) of the ball position data after the ball release plotted against time. The ball release was determined by the moment when the distance between the ball and the hand marker's position was >10 cm, based on the ball's radius and

finger length. In addition to these parameters, the duration and distance, of which the ball traveled in the backswing phase, from *BSW* to the moment of the V_{peak} ($T_{BSW-V_{peak}}$ and $D_{BSW-V_{peak}}$) and from V_{peak} to *FWD* ($T_{V_{peak}-FWD}$ and $D_{V_{peak}-FWD}$), as well as the duration and distance that the ball traveled in the forward swing phase ($T_{forward}$ and $D_{forward}$), were also calculated.

To capture the characteristics of joint movements of the throwing arm, rotation angles of the shoulder and elbow were calculated by following a study by Feltner and Dapena (1986), as shown in Figure 4.

Based on these reference frames and vectors, the joint angles of the throwing arm were calculated as follows: the angles at the shoulder joint of abduction/adduction (Figure 4-b), horizontal abduction/adduction (Figure 4-c), internal/external rotation (Figure 4-d), and the flexion/extension angle at the elbow joint (Figure 4-e). To capture the upper trunk rotation to swing the throwing arm, the upper-trunk rotation angle was also calculated by the angle between the projection of x_1 onto the horizontal plane in the global reference frame and the axis y_g of the global coordinate system. A second-order low-pass filter filtered the above angular excursions with a cutoff frequency of 20-Hz. Angular velocity and acceleration were calculated by numerical differentiation for these angle data. From these kinematic data, the maximum angle, peak angular velocity, and peak positive and negative acceleration were obtained for analysis.

To capture the timing of the above movements, the relative timing of the maximum/minimum angle, velocity, and acceleration of the joint movements was obtained by calculating the ratio of the time between these kinematic landmarks and the moment of the shoulder's maximum external rotation (Figure 1-13) to the duration of the backswing phase, determined as the time from the moments of the lowest position (Figure 1-2) to the moment of the maximum external rotation (Figure 1-13).

Statistical Analysis

Using the above ball kinematic parameters, correlation analysis was conducted between the forward swing parameters ($V_{release}$, $A_{forward}$, $D_{forward}$, and $T_{forward}$) as a dependent variable and the backswing parameters (V_{peak} , A_{min} , $T_{BSW-V_{peak}}$, $D_{BSW-V_{peak}}$, $T_{V_{peak}-FWD}$, and $D_{V_{peak}-FWD}$) as independent variables. Thereby, the researchers attempted to identify the ball parameters in the backswing phase that are associated with the forward swing movement to deliver the high-speed pitch.

To capture the characteristics of shoulder and elbow joint movement, which are related to the ball's kinematic parameters in the backswing phase, correlation analysis was conducted between the kinematic variables of the shoulder and elbow joint movements as well as the upper-trunk rotation and the key backswing ball parameters identified by the ball parameters' correlation analysis. For the correlation analysis, the mean values of the ball and joint kinematic parameters were obtained for each ball speed condition for each participant and subjected to across-participant analysis. Pearson correlation was obtained by statistical analysis software (SPSS Statistics 17.0), and we regarded $r > 0.7$ as high correlation and $0.5 < r < 0.7$ as moderately high correlation.

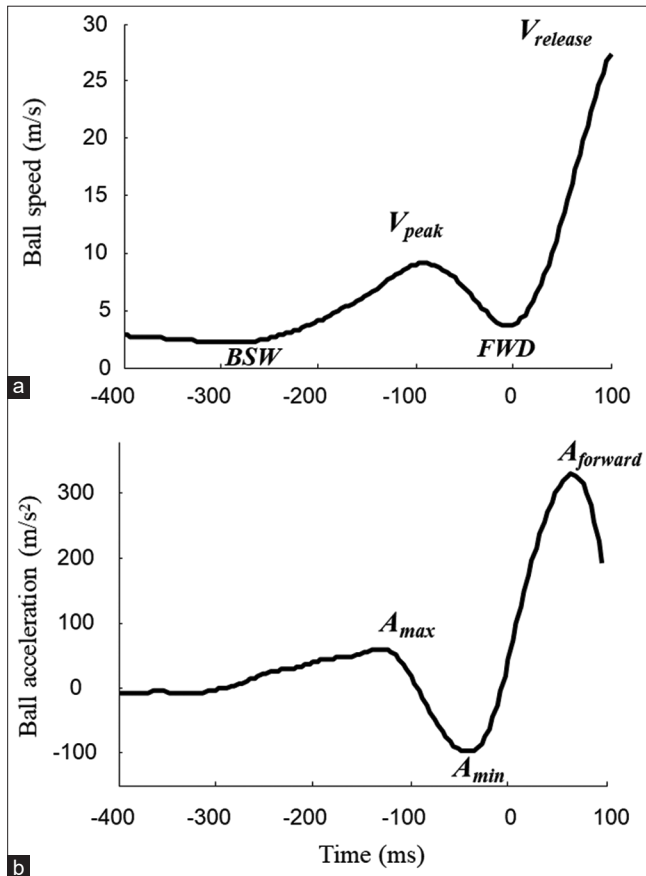


Figure 3. The speed (A) and acceleration (B) of the ball were plotted over time to the moment of the ball release (Figure 1-18). The change of the ball speed from *BSW* to *FWD* occurred during the backswing phase, which was defined to be from the moment of the throwing hand at the lowest position (Figure 1-2) to the moment of the maximum external rotation of the shoulder joint (Figure 1-13). Time 0 refers to the moment of *FWD*.

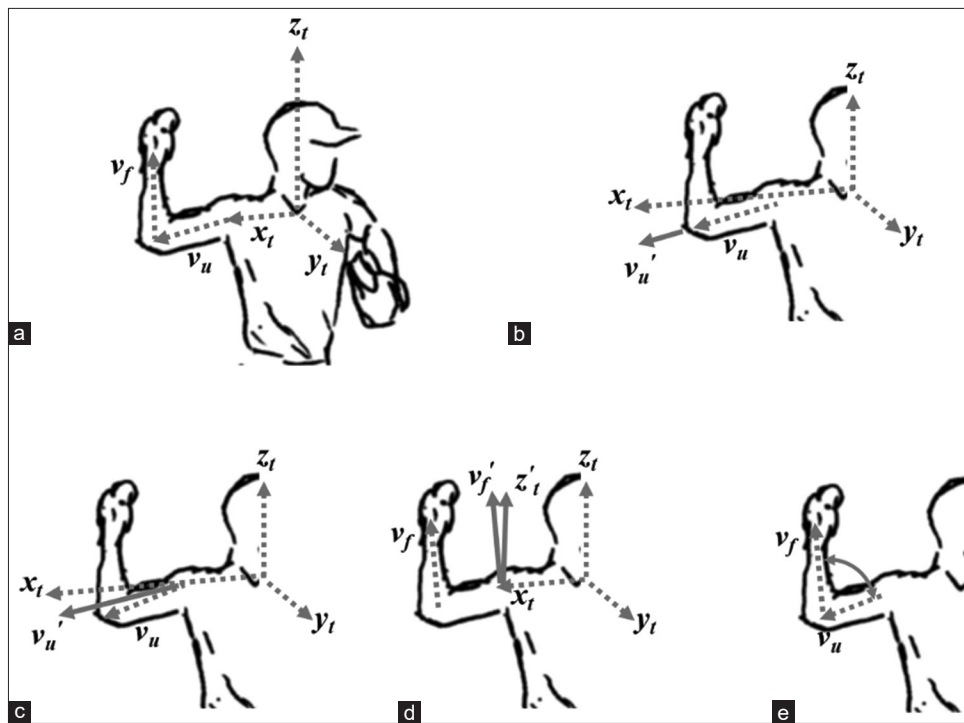


Figure 4. Joint angle definition (a) A local reference frame was defined by direction vectors x_t , y_t , and z_t (x_t : pointed from the midpoint between right and left shoulders to the right shoulder; y_t : the cross product of x_t and the vector from the middle of two shoulders to the midpoint of two hipbones; z_t : the cross product of x_t and y_t). The upper arm and forearm were described by v_u and v_f , the vectors pointing from the right shoulder marker to the right elbow marker and the vector pointing from the right elbow marker to the right wrist marker, respectively. (b) Abduction/adduction at the shoulder joint: the angle formed by x_t and v_u' , which is the projection of v_u onto the plane determined by x_t and z_t . (c) Horizontal abduction/adduction at the shoulder joint: the angle by x_t and v_u' , which is the projection of v_u onto the plane defined by x_t and y_t . (d) Internal/external rotation of the shoulder joint: the angle formed by v_f' and z_t' , which are the projection of z_t and v_f onto the plane perpendicular to the longitudinal axis of the upper arm. (E) Flexion/extension at the elbow joint: the angle formed by v_f and the reverse of v_u .

RESULTS

The table 1 showed the anthropometric characteristics of participants.

Ball Kinematic Parameters in the Backswing Phase

In the forward swing phase, high pitch velocity ($V_{release}$) is produced by the arm's forward swing with a longer distance ($D_{forward}$) and/or a longer time ($T_{forward}$) for applying force to the ball and accelerating a ball ($A_{forward}$). The ball kinematic parameters in the backswing phase showed a significant correlation with these forward swing parameters as below (Table 2).

Correlation between the backswing and forward swing parameters

V_{peak} showed significantly positive high correlation with $V_{release}$ ($r = 0.75$, $p < 0.01$) and $A_{forward}$ ($r = 0.76$, $p < 0.01$). These correlations mean that the production of a higher backswing speed was associated with the higher ball's acceleration and release speed. $T_{V_{peak-FWD}}$ also showed a negative correlation with $V_{release}$ ($r = -0.72$, $p < 0.01$) and $A_{forward}$ ($r = -0.70$, $p < 0.01$), which suggests that the shorter duration from V_{peak} to FWD in the backswing was associated with the larger magnitude of the ball's acceleration and the higher ball's release speed. These correlations suggest that the shorter transition

Table 1. Anthropometric characteristics of participants (mean±sd)

Age	Weight (kg)	BMI	Year of experiences
21.6±0.8	72.1±8.7	23.5±2.6	12.5±4.4

duration from the backswing to the forward swing was associated with the ball's acceleration in the forward swing. This inference is supported by the following moderately significant correlation, which was obtained in A_{min} with respect to $A_{forward}$ ($r = -0.61$, $p < 0.01$), $T_{forward}$ ($r = 0.56$, $p < 0.01$), and $V_{release}$ ($r = -0.53$, $p < 0.01$). These correlations indicated that the larger magnitude of ball speed decrease (A_{min}) in the backswing phase was accompanied by the larger magnitude of the acceleration of the ball ($A_{forward}$) with the shorter duration of the forward swing phase ($T_{forward}$), and the higher release speed ($V_{release}$). Likewise, the correlation between $T_{V_{peak-FWD}}$ and $T_{forward}$ was also moderately significant ($r = 0.68$, $p < 0.01$), such that the shorter backswing duration ($T_{V_{peak-FWD}}$) was accompanied by shorter forward swing duration ($T_{forward}$). These results imply that abruptly switching from the backswing to the forward swing movement may be associated with the fast forward swing movement to accelerate the ball.

Correlation among the backswing parameters

Given the above results, a correlation analysis among the backswing parameters, V_{peak} , A_{min} , and $T_{V_{peak}-FWD}$ was conducted. The significant correlation was obtained between V_{peak} and A_{min} ($r = -0.80$, $p < 0.01$), and moderately significant correlations between V_{peak} and $T_{V_{peak}-FWD}$ ($r = -0.69$, $p < 0.01$), and between $T_{V_{peak}-FWD}$ and A_{min} ($r = 0.61$, $p < 0.01$). These results suggest that the higher ball speed in the backswing was accompanied by a greater magnitude of the ball's speed decrease with the shorter backswing duration.

The within-participant correlation between the backswing and forward swing parameters

In addition to the results of the across-participant analysis, the within-participant correlation was also conducted for each participant separately, using all the data from all the target ball speed conditions, and the percentage of the number of participants, whose correlation coefficients were >0.6 or <-0.6 , was reported in the table. The correlations, which showed the high and moderately high correlation coefficients in the across-participant analysis, also revealed the high percentage of participants. Therefore, the correlations by the across-participant study were confirmed for each participant to scale up and down the ball release speed.

Joint Movement of the Throwing Arm in the Backswing Phase

The patterns of joint movements across the different ball speeds ($V_{release}$)

Figure 5 shows exemplary joint kinematics of the elbow and shoulder in the backswing phase from one participant.

From the figure, it can be seen that the patterns of the joint excursion were preserved across the different ball release speeds, even though the maximum values of joint angle, angular velocity, and acceleration, as well as the timing of those kinematic events, changed systematically as the ball release speed decreased or increased. These changes across the different ball release speeds imply the arm movement was scaled up and down depending on the target ball speeds. These joint movement patterns were composed of: 1) the elbow extension, which lowered the hand (Figure 1-2), 2) the abduction, by which the arm was elevated from the lowered position (Figure 1-3 to 5), 3) the horizontal abduction to its maximum position (Figure 1-7), after which the movement was switched to the horizontal adduction, and 4) the arm's internal rotation, which was changed to the external direction. This external rotation continued further to its maximum position of the external rotation (Figure 1-13).

The relative timings of joint kinematics

The within-participant means of the relative timings were obtained for each speed condition separately, and these mean values across the participants are plotted in Figure 6. The relative timings of the maximum rotation velocity and ac-

celeration of the upper trunk and V_{peak} and FWD were also calculated and shown in Figure 6.

In Figure 6, the backswing phase started with the elbow fully extended, by which the ball's lowest position was obtained. And then, the shoulder's horizontal abduction and abduction with the elbow flexion were unfolded to the moment of V_{peak} . At around the moment of V_{peak} , the minimum negative acceleration of the elbow's flexion and the shoulder's abduction were produced. After V_{peak} , the ball's speed decreased and A_{min} occurred before the moment of FWD . During this period, the upper trunk rotation and the horizontal adduction of the shoulder was initiated, as indicated by those maximum accelerations. At around the moment of FWD , the maximum angular velocity of the horizontal adduction, which contributes the forward swing of the throwing arm, and the maximum elbow flexion occurred. These results indicate that the transition of the ball's movement direction from the back to the forward occurred when the movements of the trunk and throwing arm in the throwing direction were initiated. In addition, the maximum acceleration of the external rotation also occurred after V_{peak} and its maximum rotational velocity was at around FWD . This indicates that, while the trunk and shoulder joint started the movement for the forward swing, the arm was rotated in the opposite direction. The trunk's maximum rotational velocity occurred approximately at the moment of the shoulder's full external rotation, right after which the maximum acceleration of internal rotation, which plays a role for the forward arm swing, occurred (not shown in the figure).

Backswing Joint Kinematic Parameters Relevant to the Key Ball Parameters

Table 3 shows the results of correlation analysis conducted between the kinematic parameters of the throwing arm movement and the upper trunk rotation and the key backswing parameters (V_{peak} , A_{min} , and $T_{V_{peak}-FWD}$) identified by the first analysis. In this section, the parameters that showed a high correlation in the across-participant study with the high percentage of the number of participants in the within-participant analysis are reported below.

Elbow flexion

In the elbow flexion movement, the peak angular velocity of the flexion showed a significant negative correlation with V_{peak} ($r = -0.81$), which indicates that the quick elbow flexion speed was associated with the higher ball speed.

Shoulder abduction

In the shoulder abduction movement, the peak velocity and peak negative acceleration of the abduction were significantly correlated with V_{peak} ($r = 0.75$ and $r = -0.72$, respectively), indicating that the higher velocity, as well as the larger magnitude of the negative acceleration of abduction, was accompanied by the higher ball speed.

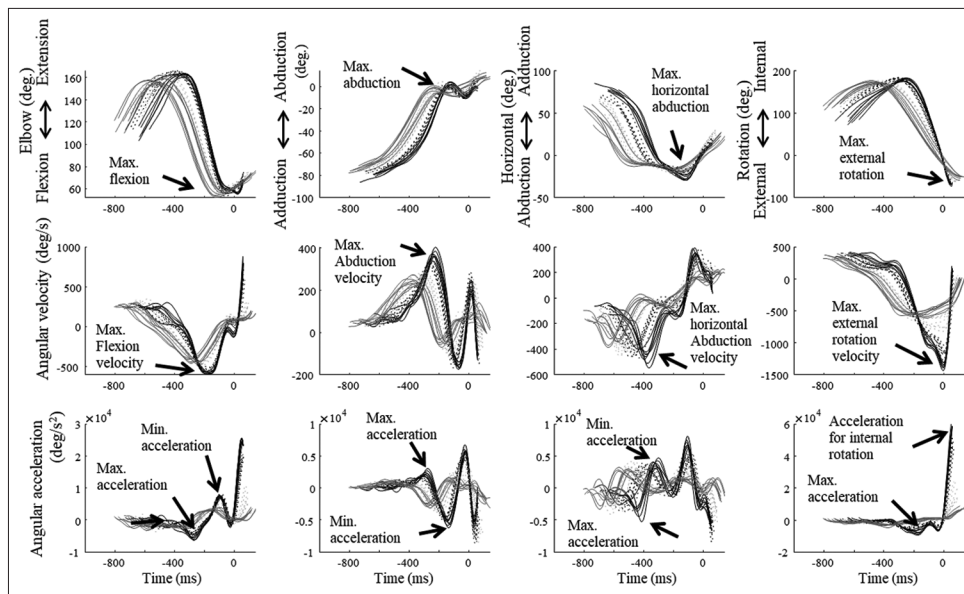


Figure 5. The joint movements from the start of a pitching movement until the maximum external rotation are shown. Time 0 indicates the moment of *FWD*. All the trials from all the speed conditions of one participant were superposed, and the dark-colored line in the figure shows the maximum speed condition.

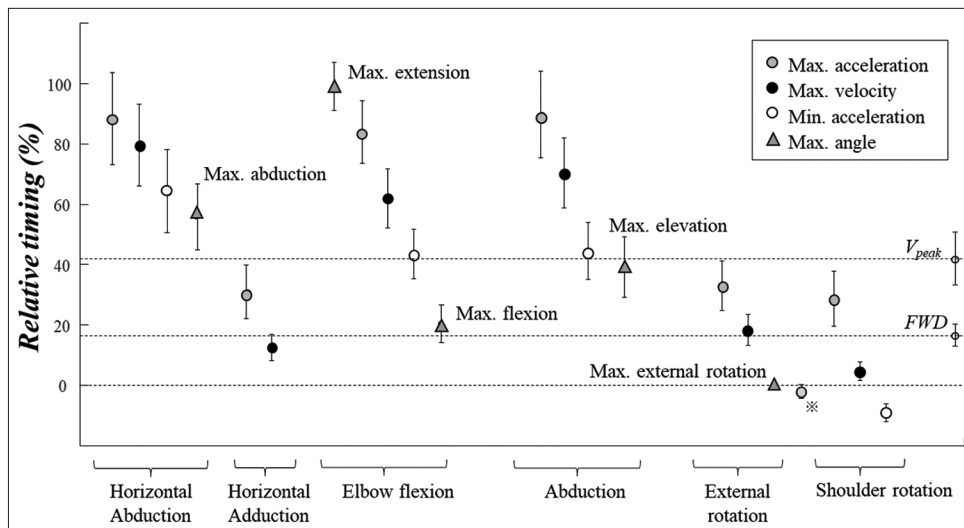


Figure 6. The gross means across the participants of the relative timings of the joint movements and upper trunk rotation regarding the backswing duration are shown. Error bars indicate the standard deviations. 0 of the y-axis corresponds to the time of the end of backswing phase, determined by the moment of the maximum external rotation. Horizontal dotted lines inserted on the figure refer to the mean relative timings of V_{peak} and *FWD*. ※After the maximum external rotation, the peak acceleration of the internal rotation occurred, which is shown in the figure.

Shoulder external rotation

In the shoulder external rotation, the significant correlation between the peak external rotation velocity and V_{peak} ($r = -0.86$) indicates that the higher ball speed was accompanied by the higher external rotation velocity. The peak external rotation velocity also showed a high correlation with A_{min} ($r = 0.76$) and $T_{V_{peak-FWD}}$ ($r < 0.75$). It should be noted that the direction of the external rotation is opposite to the throwing direction, due to which the sign of angular velocity became negative, and thereby the sign of the correlation coefficient against A_{min} was positive. These correlations indi-

cate that when the external rotation velocity became higher, the magnitude of A_{min} was more significant and the duration of $T_{V_{peak-FWD}}$ was shorter. In addition, the peak negative acceleration of the external rotation revealed a significant correlation with V_{peak} ($r = 0.71$). Due to the definition of direction for the arm’s external and internal rotation, the deceleration of the external rotation was the positive value, even though it was described as the negative acceleration. This correlation indicates that the greater decrease in the shoulder’s external rotation speed was associated with V_{peak} .

Table 2. Correlation coefficients (ccf) between the backswing and forward swing parameters of the ball kinematics

	V_{release}		A_{forward}		D_{forward}		T_{forward}	
	CCF	Percent.	CCF	Percent.	CCF	Percent.	CCF	Percent.
V_{peak}	0.75**	93	0.764**	87	0.589**	73	-0.605**	80
A_{min}	-0.53**	67	-0.613**	67	-0.198	47	0.556**	53
$D_{\text{BSW-Vpeak}}$	0.35**	33	0.350**	27	0.425**	7	-0.244	27
$T_{\text{BSW-Vpeak}}$	-0.01	13	0.059	7	0.067	7	0.028	7
$D_{\text{Vpeak-FWD}}$	-0.36**	47	-0.367**	27	0.090	27	0.473**	47
$T_{\text{Vpeak-FWD}}$	-0.72**	93	-0.696**	87	-0.436**	53	0.682**	93

** : $p < 0.01$, * : $p < 0.05$, $N = 60$

Upper trunk rotation

In the correlation between V_{peak} and the upper trunk's peak acceleration and velocity, a positive correlation was obtained. The higher V_{peak} was associated with the larger magnitudes of the rotational acceleration ($r = 0.75$) and velocity ($r = 0.75$). Likewise, the high correlations between these peak acceleration and velocity and $T_{\text{Vpeak-FWD}}$ ($r = -0.71$ and $r = -0.76$, respectively) indicate that the higher these acceleration and velocity, the shorter the duration from the moment of V_{peak} to *FWD* in the backswing movement.

DISCUSSION

Implications about the Effective Backswing Movement for the High Speed of the Pitch

This study examined the correlation and relative timing of the ball and joint kinematics in the backswing movement of baseball pitching to identify what movement parameters in the backswing phase are associated with the speed of pitches. Significant correlations were obtained between V_{peak} , A_{min} , and $V_{\text{peak-FWD}}$, backswing parameters and the forward swing parameters of V_{release} and A_{forward} (Table 2). These results indicate that the higher speed of V_{release} , the larger magnitude of A_{min} , and the shorter duration of $T_{\text{Vpeak-FWD}}$ in the backswing motion phase were associated with the larger magnitude of A_{forward} and the higher speed of V_{release} in the forward swing phase. These results suggest a possibility of V_{peak} , A_{min} , and $T_{\text{Vpeak-FWD}}$ as key parameters of the backswing movement, such that moving a throwing arm to obtain higher ball speed for the backswing and switching swiftly to the forward swing motion may contribute to the acceleration of the forward swing, thereby achieving higher release speed. Furthermore, the associations of these ball parameters with the kinematic parameters of the arm and upper trunk rotations were identified, such as the peak angular velocity of the elbow flexion, the peak velocity and negative acceleration of the shoulder abduction, the peak velocity, and negative acceleration of the external rotation, and the upper trunk's peak acceleration and velocity (Table 3). The temporal patterns of these elbow and shoulder joint kinematics associated with the moment of V_{peak} , A_{min} , *FWD*, and the upper trunk rotation were revealed by the relative timing of those parameters (Figure 6). Since these correlation results themselves do not indicate cause and effect relationships, the meaning of the correlations is considered in light of the relative timings of these param-

eters and the implications of the patterns of backswing movement for producing the pitch's speed discussed below. As a visual aid of the movement images, Figure 7 shows stick figures of the trunk and arms at key kinematic events.

The backswing movement was initiated from the elbow joint's extended and the upper arm's internally rotated posture (Figure 7-1) and unfolded by the shoulder's horizontal abduction and abduction with the elbow flexion movement (Figure 7-4). During these movements, the ball's speed reached V_{peak} (Figure 7-7) as the shoulder's horizontal abduction was completed, and the abduction and elbow flexion speed decreased. According to the correlation analysis, the higher or lower peak angular velocities of the elbow's flexion and the shoulder's abduction were followed by the higher or lower V_{peak} . These correlations appear to reflect the biomechanics of a limb's movement composed of multiple joint rotations (Putnam, 1991). A movement of the distal segment results from the effect of more proximal segments' rotations. Likewise, the negative correlation between the peak negative acceleration of the shoulder's abduction and V_{peak} may also reflect the mechanism of an open-linked kinetic chain, such that the speed of the endpoint of limb segments' links is accelerated when the rotation of the proximal segment is decelerated (Chu, Jayabalan, Kibler, & Press, 2016; Seroyer et al., 2010). Based on this, the results of the above correlation can be interpreted such that flexing the elbow and abducting the shoulder swiftly to reach the arm configuration, which appeared as the maximum angles, may be key elements of the backswing to produce the higher ball's velocity.

Subsequently to V_{peak} , the ball speed decreased to reach (A_{min}), and the movement direction started to switch to the forward swing (*FWD*: Figure 7-10). According to the relative timing during this phase, from V_{peak} to *FWD*, the upper trunk's counterclockwise rotation accelerated and reached its peak velocity (Figure 7-9 and 11), and the shoulders' external rotations were initiated and unfolded (Figure 7-6 and 8) to the maximum angle of the external rotation (i.e., the end of the backswing phase: Figure 7-12). These movements indicated that the forearm was rotating backward while the trunk was rotating forward already, and the ball's movement was switching to the forward direction. This arm's counter-movement against the trunk rotation has been known as the late cocking phase (Aguinaldo, Buttermore, & Chambers, 2007; Escamilla et al., 2001; Fleisig, Barrentine, Zheng, Es-

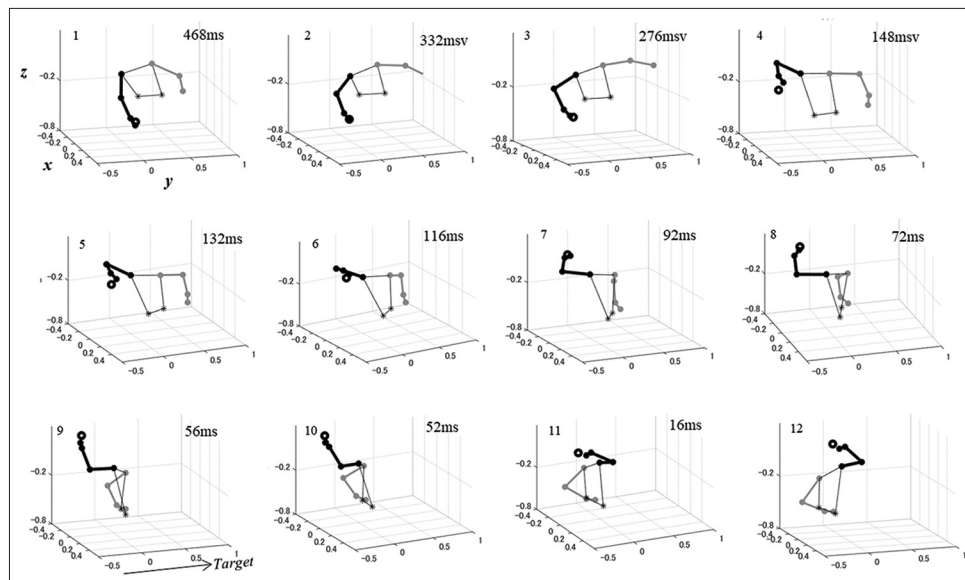


Figure 7. Each of the figures indicates the moment of the following kinematic events. The axis of x, y, and z corresponds to the definition of the global coordinate in Figure 2. Time (ms) in the figure is the time before the maximum external rotation (i.e., the end of the backswing phase). 1: Elbow's maximum extension, 2: Abduction maximum velocity, 3: Elbow's maximum flexion velocity, 4: Elbow's maximum flexion, 5: Minimum Abduction Acceleration, 6: External rotation's minimum acceleration, 7: V_{peak} and Horizontal abduction's maximum acceleration, 8: External Rotation's maximum velocity, 9: Upper trunk rotation's maxim acceleration, 10: *FWD*, 11: Upper trunk rotation's maximum velocity, and 12: Maximum external rotation, followed by the maximum acceleration of the internal rotation.

Table 3. Correlation coefficients between the joint kinematic and ball parameters

		V_{peak}	%	A_{min}	%	$T_{V_{peak-FWD}}$	%
Elbow flexion	Peak acceleration of the flexion	-0.68	67	0.59	60	0.50	67
	Peak velocity of the flexion	-0.81	73	0.65	53	0.56	67
	Peak negative acceleration of the flexion	0.60	60	-0.70	27	-0.52	53
	Maximum flexion	-0.18	27	0.36	27	0.07	20
Shoulder abduction	Peak acceleration of the abduction	0.58	67	-0.52	33	-0.37	40
	Peak abduction velocity	0.75	73	-0.68	47	-0.50	53
	Peak negative acceleration of the abduction	-0.72	100	0.75	53	0.62	87
	Maximum abduction	0.44	73	-0.53	47	-0.31	60
Shoulder horizontal abduction	Peak acceleration of the horizontal abduction	-0.58	7	0.61	20	0.37	27
	Peak horizontal abduction velocity	-0.48	27	0.44	20	0.29	20
	Peak negative acceleration of the horizontal abduction	0.59	33	-0.71	33	-0.46	33
	Maximum horizontal abduction	0.04	27	-0.14	27	-0.04	20
Shoulder external rotation	Peak acceleration of the external rotation	-0.63	87	0.55	67	0.62	87
	Peak external rotation velocity	-0.86	87	0.76	73	0.75	87
	Peak negative acceleration of the external rotation	0.71	87	-0.51	73	-0.68	80
	Maximum external rotation	-0.58	53	0.25	40	0.41	67
Upper-trunk rotation	Peak acceleration of the upper-trunk rotation	0.75	93	-0.55	73	-0.71	87
	Peak velocity of the upper-trunk rotation	0.75	100	-0.60	73	-0.76	100

$p < 0.01$ in any of correlation coefficient, which is $r > 0.5$ and $r < -0.5$

camilla, & Andrews, 1999; Fleisig, Hsu, Fortenbaugh, Cordover, & Press, 2013). The correlation analysis showed that the higher V_{peak} was followed by the higher peak angular velocities of external rotation and upper trunk rotation and the peak acceleration of the upper trunk rotation.

According to the biomechanics of baseball pitching (Calabrese, 2013; Chu et al., 2016; Seroyer et al., 2010), the late cocking phase is induced by the effect of the inertia composed of the forearm, hand, and ball, which works against the forward movement of the upper arm and trunk. Addi-

tionally, the analysis of joint torques in a pitching arm by Feltner and Dapena (1986) and Feltner (1989) revealed that while the forearm externally rotates, joint torques for horizontal adduction and internal rotation are observed at the shoulder joint, and the upper trunk's rotation is a primary contributor to the forward rotation of the upper arm (Feltner, 1989; Feltner & Dapena, 1986). Based on this mechanism, the meaning of the correlation between V_{peak} and the external rotations and the upper trunk rotation was interpreted as follows. When V_{peak} is higher, the momentum induced by the ball-hand-forearm movement becomes larger. Therefore, the larger effect of their inertia to work against the joint shoulder movement is induced. Thereby, the position of the arm's distal segments lagged behind the trunk's forward movement, due to which the external rotation was facilitated. Therefore, the higher V_{peak} appears to be correlated with the higher peak velocity of the external rotation. Since the upper trunk rotation is a prime contributor to the arm's forward rotation, its velocity should be high enough to overcome the larger inertia of the ball-hand-arm segment. Therefore, the higher V_{peak} was accompanied by the higher peak acceleration and velocity of the upper trunk's rotation to pull the arm for the forward swing.

At around the moment of *FWD* (Figure 7-10), peak velocity of the external rotation occurred (Figure 7-8), after which rotational velocity decreased (i.e., negative acceleration) to the moment of the maximum external rotation (Figure 7-12). It should be noted that the negative acceleration of the external rotation corresponds to the positive acceleration in the direction of the internal rotation since the maximum external rotation switched to the internal rotation and the peak value of this rotational acceleration occurred within this transition from the external to the internal rotation (the figure shows only to the moment of the maximum external rotation). This internal rotation contributes to the production of the forward arm swing movement. Since the positive value described the peak negative acceleration of the external rotation due to the definition of the rotational direction, the positive correlation, which shows that the higher V_{peak} was followed by the higher negative acceleration of the external rotation, implies that when the higher ball speed was obtained, the external rotation velocity decreased more abruptly to switch into the internal rotation. Additionally, the correlation analysis revealed that the higher the peak velocity of the external rotation, the larger the magnitude of A_{min} . This indicates that when the ball speed decreased more abruptly, the arm rotated faster in opposite to the throwing direction. Furthermore, the correlation analysis also revealed that the shorter backswing duration ($T_{V_{peak-FWD}}$) is accompanied not only by the higher peak velocity of the external rotation but also by the higher peak acceleration and velocity of the upper trunk rotation. These results show that the backward arm rotation, which was produced by the external rotation, changed swiftly to the internal rotation when V_{peak} was higher and A_{min} was greater and that the faster upper trunk rotation was associated with this swift transition from the external to the internal rotation. These results highlight the facilitation of a counter-movement for using a stretch-shortening cycle (Chu et al.,

2016; Remaley et al., 2015; Seroyer et al., 2010; Takagi et al., 2014), that is that, a pre-stretch effect on the shoulder's muscle group for the forward swing against the upper arm's external rotation will be induced to enhance the subsequent concentric muscle contraction for swinging the arm to throw a ball.

Limitation of Study and Recommendation for Future Studies

By focusing on the backswing movement, this study could identify the critical kinematic parameter of the movement associated with the higher pitch speed. However, a pitching movement is composed of a whole-body movement. For instance, the peak acceleration and velocity of the upper trunk rotation, which were identified as important parameters in this study, are generated by utilizing ground reaction forces (Guido & Werner, 2012; MacWilliams, Choi, Perezous, Chao, & McFarland, 1998; Oyama & Myers, 2018). Therefore, the effect of stepping movement toward the pitching direction and the rotation of the pelvis as well as the coordination of those movements with the backswing arm movement, will be an important viewpoint for future studies. Likewise, the investigation on the joint movements of the wrist and forearm's pronation and supination in the backswing phase, which was not addressed in this study, may add further knowledge to the findings in this study. From a practical viewpoint, the effect of practice to learn the backswing as suggested by the finding of this study on the improvement of the speed of the pitch is an interesting subject following this study.

Strength and Practical Implication of the Study

Based on the perspective that a multi-joint movement is organized to produce a movement of an end-point effector to achieve a performance goal (Andel et al., 2021; Kugler & Turvey, 2015; Latash, 2010 2020; Newell & Liu, 2021; Pacheco et al., 2019), this present study focused on the ball kinematics in the pitching movement to capture the kinematic features of the backswing movement. The findings were the increase of the ball speed and its abrupt deceleration for the swift switch from the backswing to the forward swing movement for the higher speed of the pitch. Thereby, $V_{release}$, A_{min} , and $T_{V_{peak-FWD}}$ were identified as the parameters which are associated with the speed of pitches. Given these parameters as keys to investigate kinematic parameters of joint arm movement in the backswing movement, the following implications were obtained from the correlation analysis and the relative timing of those parameters. For accelerating the forward swing movement and achieving the higher pitch speed, the role of backswing movement can be facilitated by swinging the pitching arm backward to induce the higher speed of a ball and switching abruptly to the forward swing movement. This movement pattern of backswing needs to be achieved by the faster movements of the elbow flexion and shoulder abduction and the coordination of these movements with the rotation of the upper trunk. In addition to it, rotating the upper trunk faster

with the arm movement reaching to the configuration of the elbow flexed and the shoulder abducted facilitates the faster external rotation of the arm at the shoulder joint. This movement pattern can enhance the abrupt switch from the backswing to the forward swing, which can potentially improve the stretch-shortening cycle of the shoulder muscles to swing the arm forward (Chu et al., 2016; Remaley et al., 2015; Seroyer et al., 2010; Takagi et al., 2014). As the practical implication for coaching and practicing baseball pitching, the above findings can be hints about how to move for an effective backswing to achieve the higher pitch speed. Based on those findings, pitchers may explore the coordination of the trunk rotation with the elbow and abduction movement and discover the movement pattern of the backswing, which can induce the higher ball's backswing speed and enhance the external rotation and switch abruptly to the forward swing. In the previous study by Katsumata et al. (2017), correlation analysis of the ball kinematic parameters between the backswing and forward swing phases was conducted, and the parameters corresponding to A_{min} in this study revealed a significant correlation with the peak acceleration ($r = -0.86$) and velocity ($r = -0.71$) of the ball in the forward swing phase. In their study, the joint kinematic parameters, which showed a significant correlation with A_{min} , were the peak negative acceleration of elbow flexion ($r = -0.79$) and the peak acceleration of external rotation ($r = -0.65$). In addition to it, the peak negative acceleration of elbow flexion also showed a significant correlation with V_{peak} ($r = 0.66$). Those correlation results were similar to what this study obtained. However, the more kinematic parameter with $r > 0.6$ or $r < -0.6$ were obtained in this study, and thereby, the characteristic of the pattern of backswing movement associated with the speed of pitch could be elucidated more clearly in this study. This may be due to the design of task conditions such that ten pitchers' maximum speed pitches were subjected to the analysis in their study, while fifteen pitchers' different speeds of pitches (from 40% to the maximum) were analyzed in this study.

CONCLUSION

The results obtained by the correlation and relative phase of kinematic parameters of the ball and arm movements in the backswing phase imply that the swift movement of the shoulder abduction and the elbow flexion from a posture with the elbow extended and the arm internally rotated are key elements of the backswing movement to produce the higher V_{peak} , which induces the larger effect of the inertia of the arm's distal segments to enhance the effect of counter-movement by the external rotation. The temporal coordination of the external rotation with the rotation of the upper trunk, and the production of the upper trunk's rotation velocity, which is high enough to resist the arm-and-ball inertia, are also key elements for the abrupt switch from the backswing to the forward swing of the arm. This backswing–forward swing transition may accelerate the ball to obtain a higher release speed.

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