Upper Limb Kinetics Difference between Pitchers with Different Pitch Velocities in Baseball Pitching Motion

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球速の異なる野球投手のピッチング動作における上肢キネティクスの違い

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和文抄録

本研究の目的は，球速の異なる野球投手のピッチング動作における上肢キネティクスを時系列データを用いて比較し，関節トルク，関節力の発揮のタイミングやボール速度との関係を検討することであった．22名の被験者について，キネマティクスおよびキネティクスデータを算出した。球速の大きな投手群（HG）は小さな投手群（LG）に比べて有意に大きな体幹の捻転および肩関節水平内転のトルク，角速度およびトルクパワーを発揮していた．そして，これらのパラメータは球速と有意な正の相関を示した．これらのことから，球速を大きくするには肘関節や手関節の関節力パワーを大きくするとともに，体幹の捻転および肩関節水平内転のトルクパワーを大きくすることが重要である．そしてこれを行うためには，踏込脚接地後の体幹の前方への捻転および肩関節水平内転の角速度を大きくすることが重要である．

キーワード：野球のピッチング，キネティクス，時系列データ，体幹の捻転，肩関節の水平外転

Abstract

The aims of this study were to compare the upper limb kinetics of different ball velocity pitchers using time-series data, and to determine the relationship between magnitude of and timing to exert joint torque, joint force, and ball velocity. A total of 22 subjects were studied and calculated kinematic and kinetic data. High ball velocity group (HG) exerted significantly larger forward torsion and shoulder horizontal adduction torque, angular velocity and joint torque power than low ball velocity group (LG), and these parameters showed a significant positive correlation with initial ball velocity. These results indicate that in order to increase initial ball velocity, it is important to increase the joint torque power of the trunk and the horizontal adduction torque power of the shoulder joint, as well as the joint force power of the elbow and wrist joints. In order to accomplish these things, increasing the angular velocity to achieve forward torsion of the trunk and horizontal adduction at the shoulder joint after stride foot contact is important.

Key words：Baseball pitching, Kinetics, Time-series data, Trunk Torsion, Shoulder horizontal adduction

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Introduction

A pitcher plays a pivotal position in baseball in securing victory. Among the factors determining a pitcher's ability, throwing a fastball is considered to be the most important. A number of studies on pitching motion have been conducted to date, particularly on upper limb kinematics (Dillman et al., 1993; Pappas et al., 1985; Sakurai et al., 1993; Fleisig et al., 1995; Miyanishi et al., 1996; Matsuo et al., 2001; Takahashi et al., 2005). There have also been several studies on upper limb kinetics (Feltner and Dapena, 1986; Feltner and Dapena, 1989; Feltner, 1989; Werner et al., 1993; Fleisig et al., 1995; Miyanishi et al., 1997), and a large part of their objective is to reveal the mechanism of pitching motion or identify the cause of injury. On the other hand, there are only a few studies that have examined joint torque and joint force and related variables, which are exerted during pitching motion by different ball velocity pitchers. It is thus important to evaluate joint torque or joint force using time-series data, since proper timing may increase ball velocity even with low torque exerted at a joint. In fact, ball velocity does not necessarily increase with increasing joint torque or joint force exerted during pitching motion.

The aims of this study were to compare the upper limb kinetics of different ball velocity pitchers using time-series data and to determine the relationship between magnitude of and timing to exert joint torque and joint force, and ball velocity.

Methods

Data Collection and Data Processing

A total of 22 subjects were studied, which included 9 amateur baseball pitchers, 10 university baseball pitchers and 3 fielders (18 right-handers and 4 left-handers; all throw overhand pitches). Sufficient explanation was provided to all subjects regarding the objectives of the study, including safety and related topics prior to the trial. Consent to participate in the study was also obtained. Following sufficient warming-up exercise, an elastic tape was attached on measuring points on the body of the subjects. Then, they were asked to throw 3－5 straight pitches at full effort to catchers in a sitting position from a regular mound.

Pitching motion was filmed using 2 MEMRECAM C2S (shooting speed, 200 frames/s) from Nac Image Technology., Inc. for amateur baseball pitchers, and 2 HSV-500 C3 (shooting speed, 250 frames/s) for university baseball pitchers. The shutter speed was set to 1/2000s.

The trial showing the highest ball velocity was used for analysis. The motion ranging from the 10th frame at the back of the point where the knee joint of the stride foot is raised highest to the 10th frame forward from the release of a ball was designated as a digitizing interval for each subject. A total of 26 measuring points including 8 upper limb points (heads of the third metacarpal of the right and left hands, wrist joint center, elbow joint center, and shoulder joint center), 12 lower limb points (toes on the right and left feet, heads of the third metatarsal bone, heel, foot joint center, knee joint center, hip joint center), 5 points of the head and trunk (top of the head, center between the right and left tragions, upper margin of the sternum, and lower end of the right and left rib bones) and the center of a ball, were digitized using FrameDias from DKH, calculating the three-dimensional coordinates of these measuring points using the Direct Linear Transformation (DLT) method. Then, optimum cutoff frequency (5～15Hz) was determined for every measuring point to perform smoothing using a Butterworth digital filter. In this study, coordinates at rest comprising the Y-axis (the vector from the center of the slab to the center of the home plate), Z-axis (vertical axis), and X-axis (the vector indicating the third base direction perpendicular to the Y- and Z-axes), was set up.

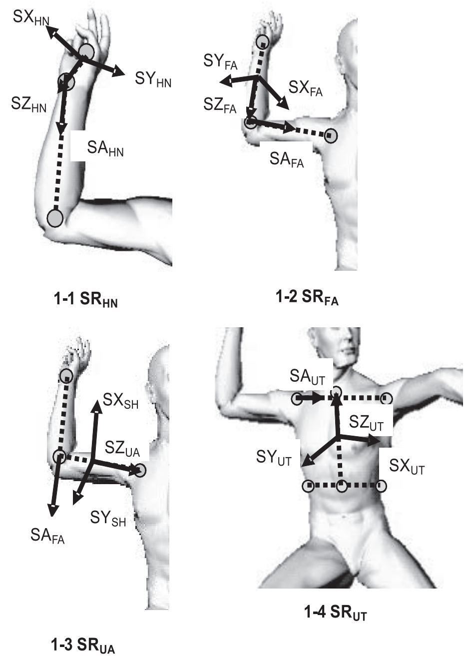

Figure 1 Definition of segment coordinates

Calculation Methodology of Upper Limb and Trunk Kinetics

Definition of Segment Coordinates

In this study, a right-handed moving coordinate was defined for each body segment of the forearm, upper arm and upper trunk, as shown in Figure 1. The outline of the method for defining the moving coordinates is given below, provided however that every vector represents a unit vector:

(1) **SR_{HN}**: a vector from the metacarpal phalangeal joint (MP) of the third finger to the right wrist joint is defined as **SZ_{HN}**. A vector from the right wrist joint to the right elbow joint is defined as **SA_{HN}**. **SY_{HN}** was calculated as the vector product of **SZ_{HN}** and **SA_{HN}**, while **SX_{HN}** was calculated as the vector product of **SY_{HN}** and **SZ_{HN}**. Although any coordinates cannot be calculated using this method when **SZ_{HN}** and **SA_{HN}** were held in alignment, they did not take such a position in an analytical phase of this study.

(2) **SR_{FA}**: a vector from the right wrist joint to the right elbow joint was defined as **SZ_{FA}**. A vector from the right elbow joint to the right shoulder joint was defined as **SA_{FA}**. **SY_{FA}** was calculated as the vector product of **SZ_{FA}** and **SA_{FA}**. **SX_{FA}** was calculated as the vector product of **SY_{FA}** and **SZ_{FA}**. Although any coordinates cannot be calculated using this method when **SZ_{FA}** and **SA_{FA}** were held in alignment, they did not take such a position in the analytical phase of this study.

(3) **SR_{UA}**: a vector from the right elbow joint to the right shoulder joint was defined as **SZ_{UA}**. A vector from the right wrist joint to the right elbow joint was defined as **SA_{UA}**. **SY_{UA}** was calculated as the vector product of **SZ_{UA}** and **SA_{UA}**. **SX_{UA}** was calculated as the vector product of **SY_{UA}** and **SZ_{UA}**.

(4) SR_{UT}: a vector from the midpoint of the lower end of the right and left rib bones to the upper margin of the sternum was defined as **SZ_{UT}**. A vector from the left shoulder joint to the right shoulder joint was defined as **SA_{UT}**. **SY_{UT}** was calculated as the vector product of **SZ_{UT}** and **SA_{UT}**. **SX_{UT}** was calculated as the vector product of **SY_{UT}** and **SZ_{UT}**.

Definition of Joint Coordinates

In this study, a joint reference (JR) system was placed for each joint of the upper limb and the trunk angle, as shown in Figure 2, and then joint motion was defined.

(1) With respect to the wrist and elbow joints, moving coordinates for the forearm (**SR_{FA}**), which was defined in the segment coordinates, was utilized by translating it to the wrist and elbow joints (herein referred to as **JR_{WR}** and **JR_{EL}**, respectively).

(2) With respect to the shoulder joint, a vector from the right elbow joint to the right shoulder joint was defined as **JZ_{SH}**. A vector from the lower end of the right rib bone to the right shoulder joint was defined as **JA_{SH}**. **JY_{SH}** was calculated as the vector product of **JZ_{SH}** and **JA_{SH}**. **JX_{SH}** was calculated as the vector product of **JY_{SH}** and **JZ_{SH}** (herein referred to as **JR_{SH}**).

(3) The JR system for the trunk angle was utilized by translating the moving coordinates for the upper trunk (**SR_{UT}**), which was defined in the segment coordinates, to the trunk angle (herein referred to as **JR_{TR}**).

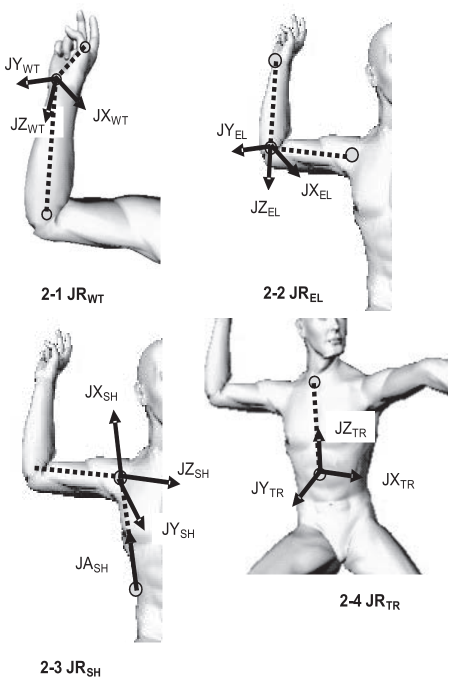

Figure 2 Definition of joint coordinates

Calculation of Joint Angular Velocity, Joint Force and Joint Torque

In this study, joint force, joint torque, joint force power, and joint torque power were calculated using the inverse dynamic method utilizing the above-mentioned segment reference and JR system in reference to the method by Shimada et al., (2004). The body segment parameters after Ae (1996) were used as an indicator of local mass, barycentric position and principal moment of inertia.

Analytical Phase and Data Normalization

In this study, an analytical phase was defined from stride foot contact (SFC) to the instant of ball release (REL) SFC and REL were determined through a video image. This time, overall motion was not divided into analytical phases at the maximum external rotation position of the shoulder joint, as seen in previous studies (Feltner and Dapena, 1986; Dillman et al., 1993; Sakurai et al., 1993; Fleisig et al., 1995; Matsuo et al., 2001). This is due to the fact that although the maximum external rotation angle of the shoulder joint is considered to be one of the most important factors for increasing ball velocity (Feltner and Dapena,1986; Feltner, 1989), it is very difficult for a coach on the ground to visually determine the point of the maximum external rotation of the shoulder joint. The time required for an analytical phase of each subject was defined as 100% with all data normalized.

Grouping of Subject and Statistical Processing

Pitchers who threw with higher velocity than the mean velocity of all subjects (34.4 ± 1.6m/s) were designated as the high-velocity group (hereinafter referred to as HG; 35.7 ± 1.0m/s, n=10). Pitchers who threw with lower velocity than the mean velocity of all subjects were designated as the low-velocity group (hereinafter referred to as LG; 33.2 ± 1.1m/s, n=12)

Two-way repeated analysis of variance (ANOVA) was performed to compare each measurement item between both groups, and to test the significance of the main effects as well as interactions (between groups × sequential change) among two groups. In this study, the causes of sequential change were not discussed since they are not part of the objectives. In the case where any interaction or main effect was observed between both groups in the analytical phase, the t-test was performed at every percent of the normalized time to determine the point of change in pattern or a significant difference. In addition, differences between both groups were tested using the t-test in terms of maximum and minimum values for measuring items and their occurrence time. The correlation coefficient between each measuring item and ball velocity at REL was calculated at every percent of the normalized time to examine for correlation. The significance level was set at $P<0.05$ for every test in this study.

Result

Velocity of Ball and Each Site of Throwing Arm

There was no significant difference in height and weight between HG and LG (HG: 1.80 ± 0.06m and 76.9 ± 5.5kg, LG: 1.77 ± 0.06m and 72.5 ± 6.8kg, respectively). However, HG showed a significantly higher initial ball velocity than LG (HG: 35.7 ± 1.0m/s, LG: 33.2 ± 1.1m/s, $p<0.001$). There was no significant difference in the amount of time required for the analytical phase between HG and LG (HG: 0.16 ± 0.02s, LG: 0.16 ± 0.03s).

Figure 3 shows the change in velocity of a ball and each joint of the throwing arm for both groups. The point when there was a significant difference between both groups is indicated by ●. The result of the two-way repeated ANOVA showed that there was a significant difference in interactions for velocity of the elbow joint, wrist joint and third metacarpal (hand) of the throwing arm and ball. The result of the subsequent t-test showed a significant difference in the region of 56～96% for the elbow joint and in the region of 78～98% for the wrist joint between both groups, with HG indicating a significantly higher velocity than LG. In addition, HG showed a significantly higher velocity than LG in the regions of 15～36% and 83～96% for the hand and 18～29% and 87～100% for the ball.

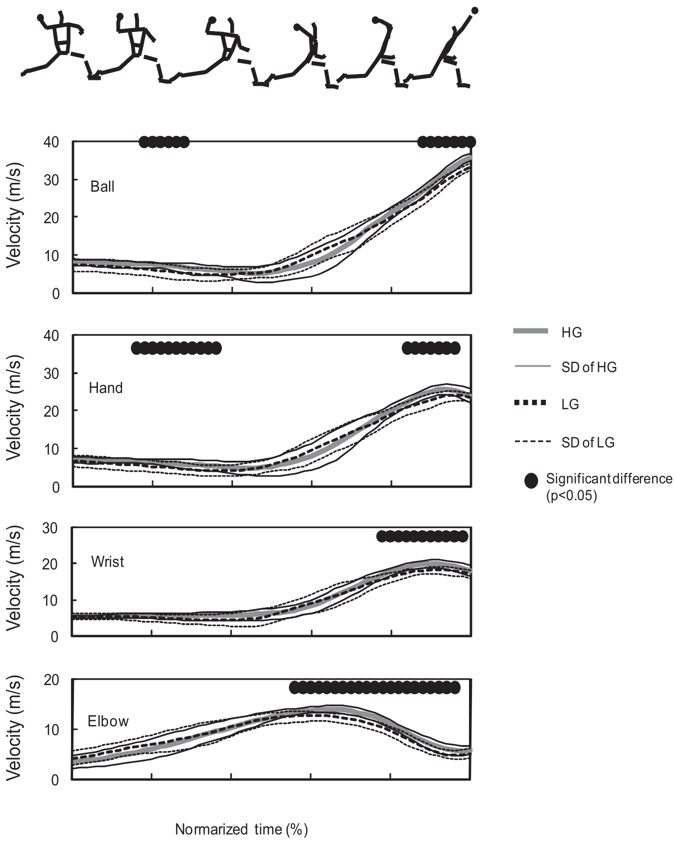

Figure 3 Resultant velocities of the ball, hand, wrist, and elbow during the analytical phase

Difference in Trunk Kinetics

Figure 4 shows the joint torque (top), joint angular velocity (second) and joint torque power (third) of the trunk joint for both groups. The left side shows the values at around the **JZTR** axis and the right side shows the total value of the three axes. The bottom side in the figure shows changes in the correlation coefficient between joint torque power and initial ball velocity at each point. The points with a thick mark are those showing a significant correlation between joint torque power and initial ball velocity.

There were significant interactions for joint torque and joint angular velocity at around the **JZTR** axis (forward torsion (+)/backward torsion (-)) and in the main effects for joint torque power at around the **JZTR** axis. The result of the subsequent t-test showed that HG had significantly higher values than LG in the joint torque at around the **JZTR** axis in the region of 68〜72%, in the joint angular velocity at around the **JZTR** axis in the region of 46〜66%, and in the joint torque power in the region of 60〜72%.

The main effect was significant in the total value of the joint torque power around each axis. The result of the subsequent t-test showed that HG had significantly higher values of composite joint torque power than LG in the region of 46〜70%. In addition, a significant positive

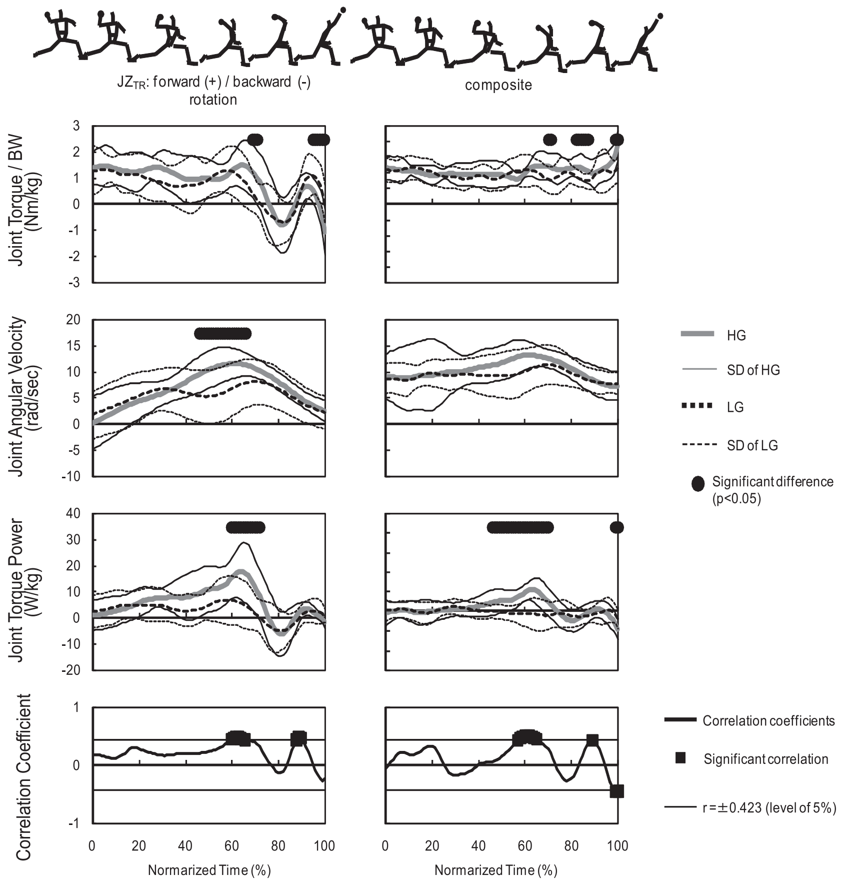

Figure 4 Joint torque, joint angular velocity, and joint torque power of the trunk about JZ_{TR} axis (left colmun) and composite value (right colmun) for HG and LG, and the correlation coefficients between each value and the ball velocity at the release

correlation between composite joint torque power and initial ball velocity was demonstrated in the region of 57～65%. With respect to the difference in composite joint torque power between both groups, that which was around the JZ_{TR} axis accounted for a large percentage.

Difference in Shoulder Joint Kinetics

Figure 5 shows the joint torque (top), joint angular velocity (second), and joint torque power (third) at the shoulder joint of both groups, and changes in the correlation coefficient between joint torque power and initial ball velocity (bottom). From the left, around the JX_{SH} axis, around the JZ_{SH} axis and composite three axes are shown.

Interactions were significant in joint torque and joint torque power at around the JX_{SH} axis (horizontal adduction (+)/ horizontal abduction (-)). The result of the subsequent t-test showed that HG exerted a significantly higher horizontal adduction torque in the region of 67～75% and a significantly higher horizontal adduction torque power in the region of 62～75% than LG. In the region of 66～74%, both groups showed a significant positive correlation

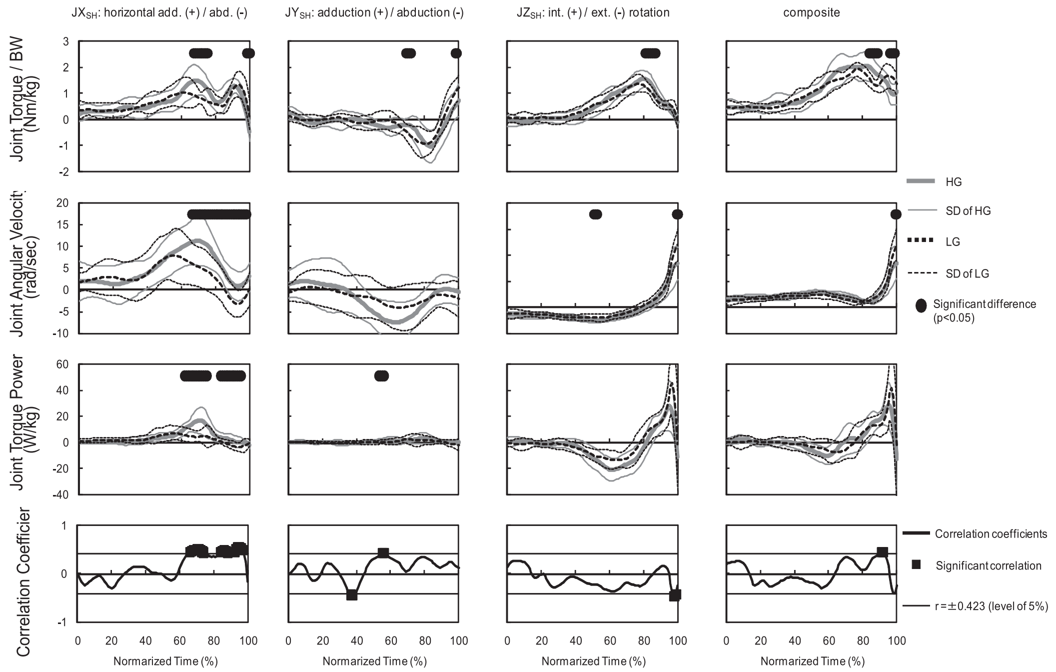

Figure 5 Joint torques, joint angular velocities, and joint torque powers of the shoulder about each axis for HG and LG, and the correlation coefficients to the ball velocity at the release

between joint torque power and initial ball velocity, respectively.

The interactions were significant in joint torque and joint torque power at around the **JZSH** axis (internal rotation (+)/external rotation (-)). The result of the subsequent t-test showed that HG exerted a significantly higher internal rotation torque in the region of 81～87% and a significantly higher negative joint torque power in the region of 58～65% than LG. However, the joint torque power at around the **JZSH** axis showed poor correlation with initial ball velocity.

Figure 6 shows the joint force (top), joint velocity (second), joint force power (third) and changes in the correlation coefficient between joint force power and initial ball velocity (bottom) at the shoulder joint for both groups. The left colmun shows the **JZSH** axial direction and the right colmun shows the composite of three axes.

The interactions were significant in joint force and joint force power acting in the **JZSH** axial direction (proximal direction (+)/distal direction (-)). The result of the subsequent t-test showed that the joint force of HG in the proximal direction was significantly higher than that of LG in the region of 53～60%, and that the joint velocity of HG was significantly higher than that of LG in the **JZSH** axial direction in the region of 38～53%. Moreover, both groups showed positive joint force power in the region of 0～75% and negative joint force power thereafter, with HG showing a significantly higher value than LG in the regions of 50～62% and 92～100%, indicating a significant positive correlation with initial ball velocity in the regions of 18～31% and 51～60%.

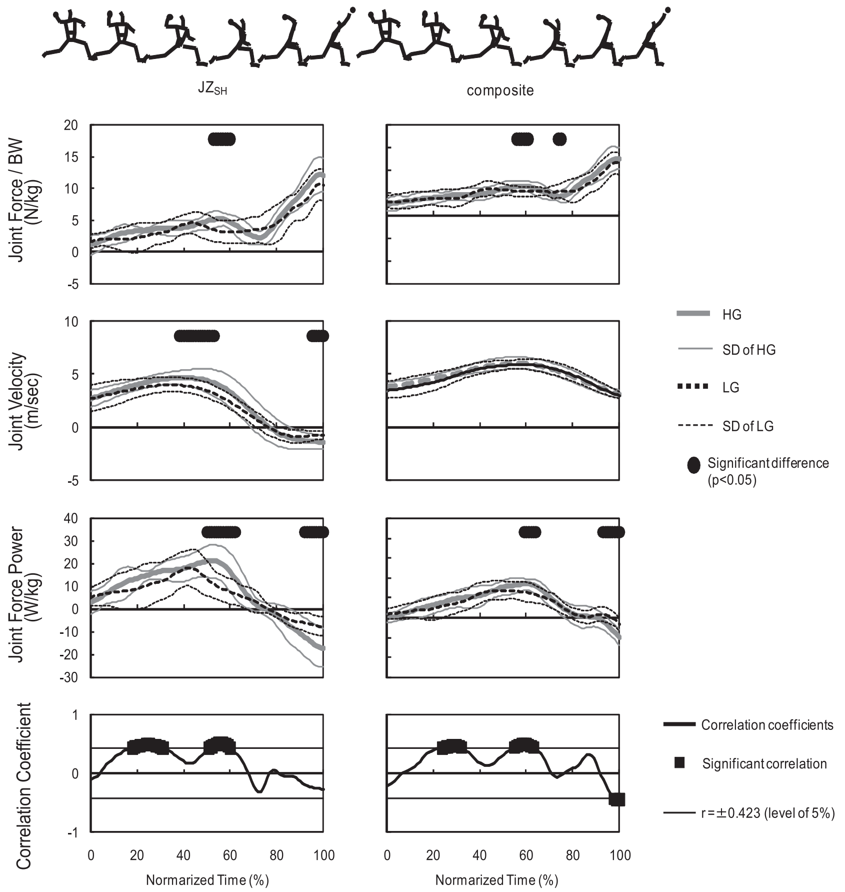

Figure 6 Joint force, joint velocity, and joint force power of the shoulder direct to the JZSH axis (left colmun) and composite value (right colmun) for HG and LG, and the correlation coefficients between the joint torque force and the ball velocity at the release

Difference in Elbow Joint Kinetics

In this study, internal and external rotation motions could not be calculated precisely since markers such as that placed on the wrist joint by Sakurai et al. (1993) or Miyanishi et al. (1996) were not used. Therefore, in terms of the elbow joint, the results for the joint torque, joint angular velocity, joint torque power and joint force, and joint velocity and joint force power at around the **JYEL** axis are shown.

Figure 7 shows the joint torque (top), joint angular velocity (second), joint torque power (third) and changes in the correlation coefficient between joint torque power and initial ball velocity (bottom) of the elbow joint for both groups at around the JYEL axis (extension (+)/flexion (-)). The interactions in joint torque, joint angular velocity and joint torque power were significant at around the **JYEL** axis. The result of the t-test for joint torque showed that HG exerted higher extension torque than LG in the region of 60～80%, and then subsequently flexion torque. In contrast, LG exerted flexion torque in the region of 70～90%, and then subsequently extension torque. HG showed a significantly higher

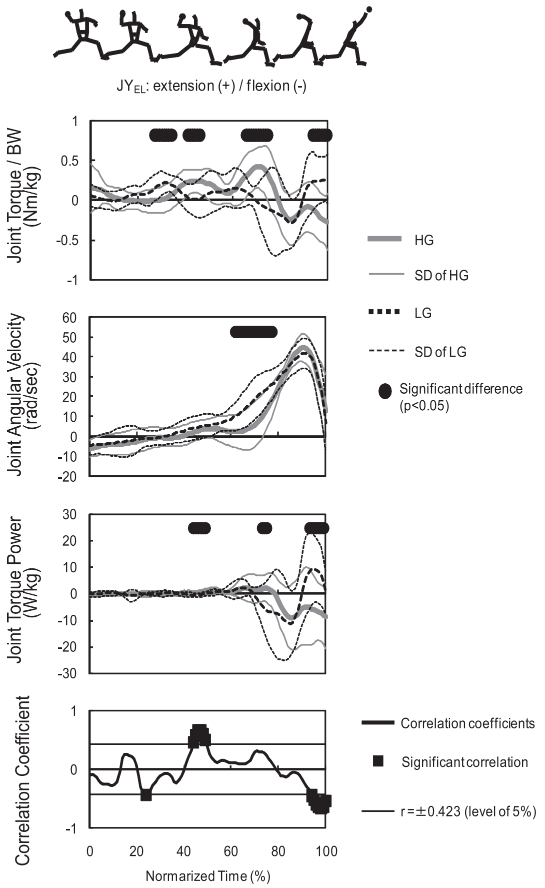

Figure 7 Joint torque, joint angular velocity, and joint torque power of the elbow about JYEL axis for HG and LG, and the correlation coefficients between the joint torque power and the ball velocity at the release

extension torque than LG in the regions of 41～46% and 66～75%. LG showed a significantly higher extension angular velocity than HG in the region of 62～77%. In terms of joint torque power, HG exerted a negative torque power from around the point of 80% to REL. In contrast, LG showed a negative joint torque power in the region of 70～90% and a positive joint torque power in the region of 90～100%. LG showed a significant negative correlation with initial ball velocity in the region of 94～100%.

Figure 8 shows the joint force (top), joint velocity (second), joint force power (third) and changes in the correlation coefficient between joint force power and initial ball velocity (bottom) at the elbow joint for both groups in the **JYEL** axial direction (inward (+)/outward (-), left colmun) and the composite power of all axial directions (right colmun).

HG exerted significantly higher inward joint force than LG in the **JYEL** axial direction in the region of 80～89%; however, any correlation with initial ball velocity was

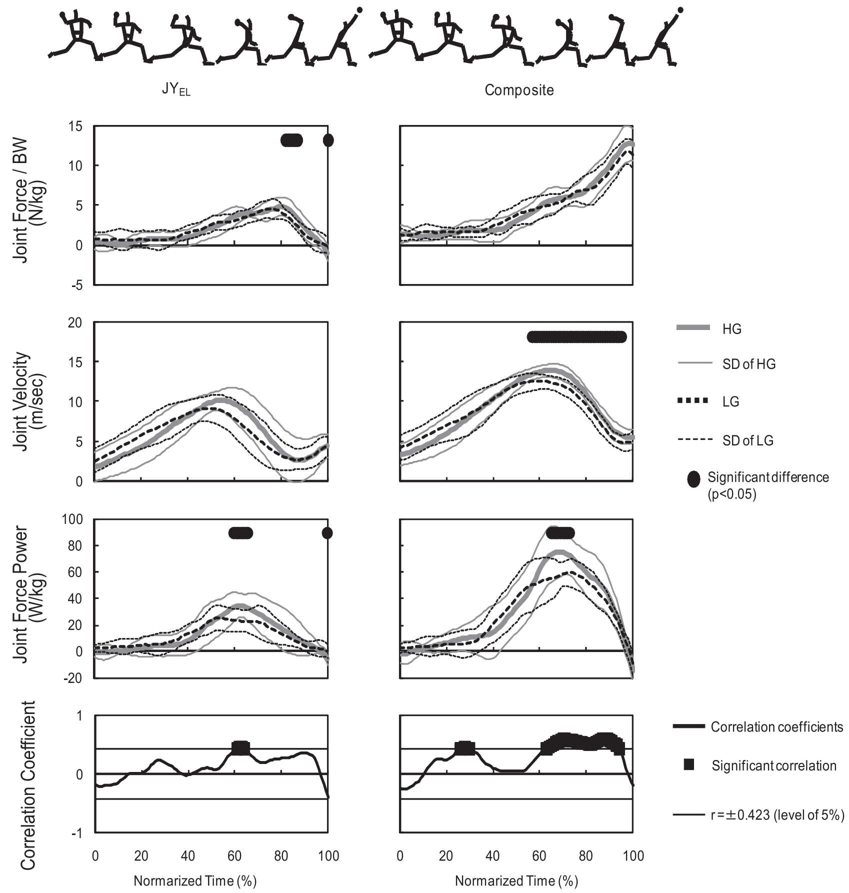

Figure 8 Joint force, joint velocity, and joint force power of the elbow direct to the JY_{EL} axis (left colmun) and composite value (right colmun) for HG and LG, and the correlation coefficients between the joint force power and the ball velocity at the release

not observed. In terms of total power, interactions were significant in every parameter of joint force, joint velocity and joint force power. The result of the subsequent t-test showed that the total joint velocity of HG was significantly higher than that of LG in the region of 57〜95%. Composite joint force power of HG was significantly higher than that of LG in the region of 65〜73%, with a significant positive correlation with initial ball velocity in the region of 63〜94%.

Difference in Wrist Joint Kinetics

In the definition of the JR system for the wrist joint in this study, the motions of palmar/dorsal flexion at the wrist joint or radial/ulnar flexion could not be exactly measured unlike in the elbow joint. Therefore, with respect to the wrist joint, the result for the joint torque at around the three axes, composite joint torque power, the joint force acting in the three axial direction, joint velocity and composite joint force power are shown.

Figure 9 shows composite joint torque (top), joint angular velocity (second), joint

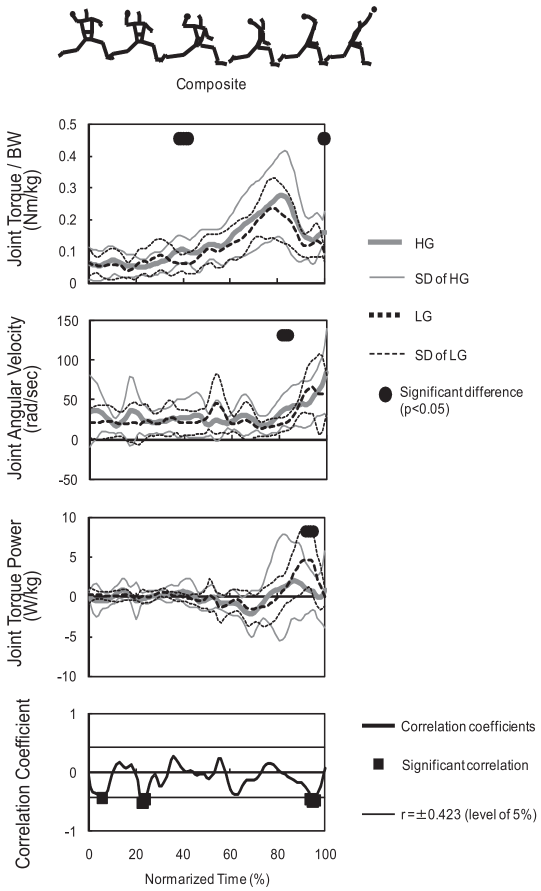

Figure 9 Composite joint torque, joint angular velocity, and joint torque power of the wrist for HG and LG, and the correlation coefficients between the joint torque power and the ball velocity at the release

torque power (third) at around the three axes at the wrist joint for both groups and changes in the correlation coefficient between joint torque power and initial ball velocity (bottom). Interactions in the joint torque of the wrist joint were not significant but those in the joint torque power were significant. The joint torque and joint torque power of the wrist joint were lower than those of the other joints.

Figure 10 shows composite joint force (top), joint velocity (second), joint force power (third) and changes in the correlation coefficient between joint force power and initial ball velocity (bottom) in the three axial direction at the wrist joint. Interactions in joint force and joint force power were significant. The result of the subsequent t-test showed that HG exerted a significantly higher joint force than LG in the region of 69～74%, and a significantly higher joint force power in the regions of 70～76% and 83～89%. HG showed a significant positive correlation between joint force power and initial ball velocity in the regions of 68～78% and 83～90%.

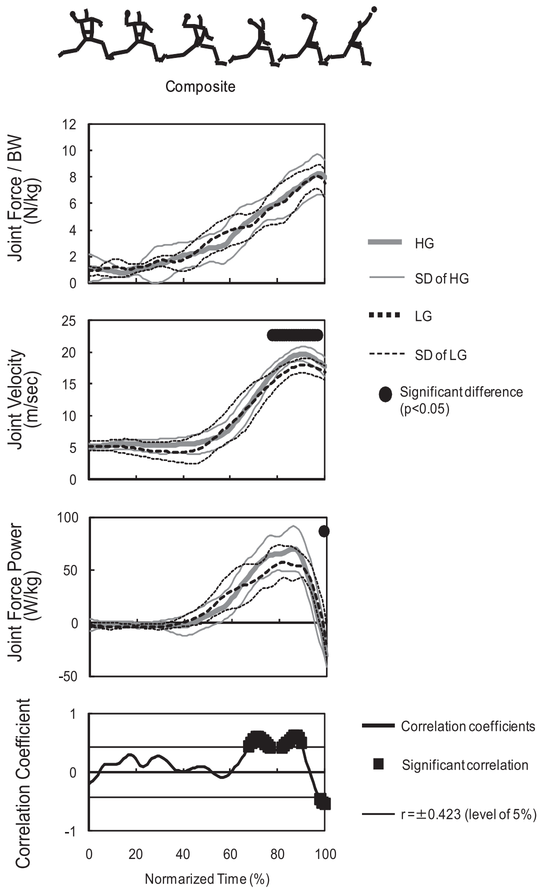

Figure 10 Composite joint force, joint velocity, and joint force power of the wrist for HG and LG, and the correlation coefficients between the joint force power and the ball velocity at the release

Discussion

Trunk Torsion

HG exerted a higher joint torque power in the trunk than LG. Among the joint torque powers exerted at the trunk angle, that at around the **JZTR** axis constituted the largest percentage. When the joint torque power reached a peak in the middle stage of the third phase, HG showed a significantly higher forward rotation angular velocity of the upper trunk than LG (Figure 4). Miyanishi et al. (1996) reported that the contribution of left rotation (forward rotation motion in this study), flexion motion of the upper trunk and horizontal flexion motion (horizontal adduction motion in this study) of the shoulder joint to the initial velocity of the ball was large in the ball synthesized (horizontal) velocity incremental phase. Given this factor, it would appear that HG exerted a high joint torque power to rotate the upper trunk forward with a high angular velocity, resulting in a high initial velocity of the ball. On the other hand, Shimada et al. (2004) described that the mechanical energy of the upper trunk markedly increased by the transfer of energy generated by the pivot leg hip joint

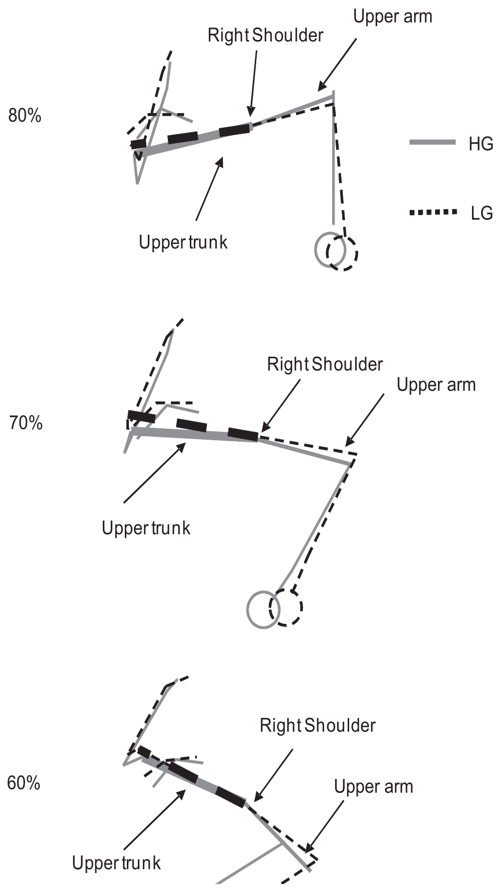

Figure11 Stick picture of HG and LG at 60%, 70%, and 80% of the normalized time from upper view

torque in the upper trunk energy incremental phase (the first half of the analytical phase in this study). In addition, Takahashi et al. (2005) reported that HG extended the hip joint of their pivot leg with a higher angular velocity than LG immediately before SFC. These findings suggest that HG transfers mechanical energy to the upper trunk via the lower trunk by effective motion of the hip joint of the pivot leg, resulting in the forward torsion of the trunk attained with a high angular velocity for a high joint torque power. Stodden et al. (2001) reported that to allow for the maximum contribution of the trunk, a pitcher needs to properly rotate the pelvis and upper trunk in the duration from cocking to the acceleration phase. Since the rotation of the upper trunk originates from the motion of the lower limbs and lower trunk, instruction should be given to produce high ball velocity with more attention given to the motions of the lower limbs and lower trunk, which are necessary for the efficient rotation of the upper trunk, than to the exertion of the joint torque of the upper trunk.

Shoulder Joint Motion

HG exerted a higher shoulder joint horizontal adduction torque, angular velocity and torque power than LG. In addition, a significant positive correlation was shown between horizontal adduction torque power and initial ball velocity around the point in which the horizontal adduction torque power shows a peak value (in the region of 70〜80%) (Figure 5). Figure 11 shows overhead stick pictures of HG and LG at the points of 60%, 70% and 80% superimposed in reference to the right shoulder. HG showed a higher horizontal abduction angle in the region of 60〜70%, with almost the same abduction angle shown at 80%. In other words, HG is considered to have accelerated the ball with the shoulder joint horizontally abducted, exerting a high horizontal adduction torque for a higher horizontal adduction angular velocity. As described above, Miyanishi et al. (1996) described that the horizontal adduction motion at the shoulder joint greatly contributed to ball acceleration. However, the preceding high horizontal abduction is considered to be important for ball acceleration.

The internal rotation torque power of the shoulder joint was found to be the highest of all joint torque powers exerted by the shoulder joint; nonetheless, no significant difference was shown between both groups (Figure 5). There was no significant difference in the maximum external rotation angle of the shoulder joint (HG: $78.9 \pm 10.7°$, LG: $82.4 \pm 9.1°$) and the internal rotation angular velocity of the shoulder joint throughout the entire phase. Instead, LG showed a significantly higher internal rotation angular velocity of the shoulder joint immediately before REL (Figure 6). As the elbow joint angle in both groups extended to about 160° immediately before REL, it would appear that the contribution of the increase in the internal rotation angular velocity of the shoulder joint to increase initial ball velocity is small. For this reason, LG presumably could not increase ball velocity despite its higher internal rotation angular velocity than HG.

In a previous study, it was reported that pitchers producing high ball velocity showed a significantly higher maximum external rotation angle of the shoulder joint and internal rotation angular velocity than those producing low ball velocity (Matsuo et al., 2001); however, the results of this study did not correlate with those of the preceding study. The possible reason for this is the fact that the difference in ball velocity between pitchers producing high ball velocity and those producing low ball velocity was smaller than that in the case of the preceding study. Nonetheless, for the pitchers equivalent to the subjects of this study, differences in ball velocity would have been due to the torsion motion of the trunk or the horizontal adduction motion of the shoulder joint or related motions, and not by the internal and external rotation motions of the shoulder joint.

Elbow Joint Motion

The elbow joint shows a higher joint force power than the trunk or shoulder joint, with the joint force power in the region of 63〜94% showing a significant positive correlation with initial ball velocity (Figure 8). Although HG exerted a negative torque power as generated by the flexion torque of the elbow joint immediately before REL, LG exerted a positive torque power generated by the extension torque of the elbow joint, with the joint torque power generated by the extension torque showing a negative correlation with initial ball velocity (Figure 7). This indicates that the extension motion of the elbow joint in this phase was greatly influenced by the motion-dependent force and not by an active motion produced by the joint torque (Feltner and Dapena, 1989; Feltner, 1989), and the results of this study support this finding. Thus, HG extended the elbow joint by exerting the motion-dependent force generated by the movement of the upper trunk and shoulder joint. On the other hand, it is considered that LG extended the elbow joint by exerting the extension torque of the elbow joint. Shimada et al. (2004) reported that the mechanical energy markedly affecting initial ball velocity in the acceleration phase (around the region of 60～100% in this study) has already been transferred into the hand by the last stage of the cocking phase (around the region of 20～60% in this study). It is thought that LG had no sufficient mechanical energy required for ball acceleration and as a result attempted to generate mechanical energy by exerting joint torque immediately before REL. Since the joint torque power at this moment showed a negative correlation with initial ball velocity, LG pitchers may be required to master the motion of the upper trunk or shoulder joint to be able to extend the elbow joint without exerting joint torque power.

Snap Action of Wrist Joint

The joint force power of the wrist joint was higher than that of the trunk or shoulder joint. In contrast, the joint torque and joint torque power of the wrist joint were lower than those of the other joints (Figures 9 and 10). HG showed a higher but not significant joint force power at the wrist joint than LG, indicating a positive correlation with initial ball velocity (Figure 10). This suggests that the wrist joint movement is largely dependent on the motion of the shoulder or elbow joints, and that the wrist joint motion represented by palmar flexion is not an active motion generated by joint torque but is produced by the joint force moment as in the elbow joint extension. Since the wrist joint moves with a high angular velocity in the end of the acceleration phase of pitching motion, the muscle group around the wrist joint cannot exert a significant muscular force. Sisto et al. (1987) measured the muscular activity of the forearm using a needle electrode when throwing straight- and curve-ball, and suggested that eccentric contraction of the flexor carpi radialis or flexor digitorum superficialis at a later stage of the cocking phase (from SFC to the maximum external rotation of the shoulder joint, or 0～80% in this study), where the wrist joint is dorsiflexed upon throwing straight-ball, allowed a slight increase in muscular activity. Fleisig (1996) described that this eccentric muscular activity prevents wrist joint hyperextension. In addition, Sisto et al. (1987) reported that the palmar flexion muscle group and dorsal flexion muscle group of the wrist joint showed almost the same muscular activity in the acceleration phase (80～100% in this study). Saito et al. (2001) showed that to prevent excess palmar flexion of the wrist joint, wrist joint immobilization is necessary by contraction of the flexor muscle of the wrist and the extensor carpi radialis, since the flexor digitorum superficialis and flexor digitorum profundus affect wrist joint palmar flexion concurrently with flexion of the interphalangeal joints. Given this factor, it is recommended to control the "wrist snap," often stressed in coaching in the phase from SFC to REL. This is taken from the viewpoint of "immobilizing the wrist joint" by contraction of the palmar flexion muscle group or dorsal flexion muscle group to some extent, in view of the fact that the dorsal flexion motion of the wrist joint seen in this phase is produced by acceleration of the forearm in a pitching direction due to the horizontal adduction motion or external rotation motion of the shoulder joint. Palmar flexion motion is produced by the motion dependent force generated by deceleration of the forearm due to the rapid decrease in the extension angular velocity of the elbow joint.

Conclusions

The aims of this study were to compare the upper limb kinetics of different ball velocity pitchers using time-series data and to examine the factors responsible for differences in ball velocity due to the magnitude of and timing to exert joint torque and joint force. The results of this study and their implications are summarized as follows:

1) HG exerted a significantly higher forward torsion torque, angular velocity and joint torque power at the trunk angle than LG in the middle stage, with these parameters showing a significant positive correlation with initial ball velocity.

2) HG exerted a higher horizontal adduction torque, angular velocity and joint torque power at the shoulder joint than LG, with the horizontal adduction torque power showing a significant positive correlation with initial ball velocity. Although the shoulder internal rotation torque power was the largest of all the joint torque powers, there was no significant difference between both groups.

3) HG exerted a negative joint torque power as generated by the flexion torque at the elbow joint immediately before REL. On the other hand, LG exerted a positive joint torque power generated by the extension torque. The elbow joint extension torque power immediately before REL showed a negative correlation with initial ball velocity. In addition, joint force power showed a positive correlation with initial ball velocity at the elbow joint.

4) Joint torque power of the wrist joint is much lower than that of the other joints; however, the joint force power of the wrist joint is higher than that of the other joints. Moreover, the joint force power of the wrist joint showed a positive correlation with initial ball velocity.

These results indicate that in order to increase initial ball velocity, it is important to increase the joint torque power of the trunk and the horizontal adduction torque power of the shoulder joint, as well as the joint force power of the elbow and wrist joints. In order to accomplish these things, increasing the angular velocity to achieve forward torsion in the trunk and horizontal adduction at the shoulder joint after SFC is important.

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