©Journal of Sports Science and Medicine (2014) **13**, 742-750
http://www.jssm.org

Research article

Kinematic and Kinetic Profiles of Trunk and Lower Limbs during Baseball Pitching in Collegiate Pitchers

Masahiro Kageyama [1], Takashi Sugiyama [1], Yohei Takai [2], Hiroaki Kanehisa [2] and Akira Maeda [2]✉
[1] Graduate School of Physical Education, National Institute of Fitness and Sports in Kanoya, Kagoshima, Japan
[2] National Institute of Fitness and Sports in Kanoya, Kagoshima, Japan

Abstract
The purpose of this study was to clarify differences in the kinematic and kinetic profiles of the trunk and lower extremities during baseball pitching in collegiate baseball pitchers, in relation to differences in the pitched ball velocity. The subjects were 30 collegiate baseball pitchers aged 18 to 22 yrs, who were assigned to high- (HG, 37.4 ± 0.8 m·s^{-1}) and low-pitched-ball-velocity groups (LG, 33.3 ± 0.8 m·s^{-1}). Three-dimensional motion analysis with a comprehensive lower-extremity model was used to evaluate kinematic and kinetic parameters during baseball pitching. The ground-reaction forces (GRF) of the pivot and stride legs during pitching were determined using two multicomponent force plates. The joint torques of hip, knee, and ankle were calculated using inverse-dynamics computation of a musculoskeletal human model. To eliminate any effect of variation in body size, kinetic and GRF data were normalized by dividing them by body mass. The maxima and minima of GRF (Fy, Fz, and resultant forces) on the pivot and stride leg were significantly greater in the HG than in the LG ($p < 0.05$). Furthermore, Fy, Fz, and resultant forces on the stride leg at maximum shoulder external rotation and ball release were significantly greater in the HG than in the LG ($p < 0.05$). The hip abduction, hip internal rotation and knee extension torques of the pivot leg and the hip adduction torque of the stride leg when it contacted the ground were significantly greater in the HG than in the LG ($p < 0.05$). These results indicate that, compared with low-ball-velocity pitchers, high-ball-velocity pitchers can generate greater momentum of the lower limbs during baseball pitching.

Key words: Throwing movement, pitching ball velocity, ground-reaction force, lower limbs, pivot and stride legs.

Introduction

In baseball, the role of the pitcher is critical and a high velocity of pitched balls is particularly important for game outcomes. The pitching motion is a highly demanding athletic skill involving fine coordination of all body segments (Atwater, 1979), and the mechanics of the lower limbs are also recognized as an integral part of the pitching motion (Mac Williams et al., 1998; Matsuo et al., 2001; Robb et al., 2010). The contributions of the lower extremities to baseball pitchers and their related motions have been described as the open kinetic chain (Kreighbaum and Barthels, 1985), in which all body segments are required to move the upper-extremity joints into appropriate positions in order to minimize the loads on each segment and transmit the generated force from the legs to more distal segments (Kibler, 1995). The lower extremities and trunk provide the beginning of the open kinetic chain that ends with force transmission to the baseball at the time of its release (Elliott et al., 1988; Mac Williams et al., 1998; Matsuo et al., 2001). Furthermore, the lower limbs have been considered to be important for constructing a stable base in which arm motion can be more efficiently and safely generated, along with providing rotational momentum (Burkhart et al., 2003; Kibler, 1991).

The mechanism of the kinetics of the lower limbs during pitching has been examined by measuring ground-reaction forces (GRF). Elliott et al. (1988) suggested that the ability to drive the body over a stabilized stride leg is a characteristic of high-ball-velocity pitchers. Mac Williams et al. (1998) reported that the maximum GRF values in the pitching direction were 0.35 and 0.72 per body weight for the pivot and stride legs, respectively, and wrist velocity at the time of ball release was related to both these variables. These findings indicate that greater GRF are necessary to throw a ball at a greater velocity. In high-ball-velocity pitchers, however, which joint of lower limbs contributes to generate a greater pitched ball velocity remains question. Thus, to clarify differences in the kinematics and kinetics of lower limbs as well as trunk during pitching between high- and low-ball-velocity pitchers may provide important knowledge concerning training and technical guidance for increasing ball velocity during pitching.

The purpose of this study was to clarify differences in the kinematic and kinetic profiles of the trunk and lower limbs during baseball pitching in collegiate baseball pitchers, in relation to differences in the pitched ball velocity.

Methods

Subjects

Thirty male collegiate baseball pitchers voluntarily participated in this study. Descriptive data on the physical characteristics of the subjects are shown in Table 1. Twenty-five subjects were right-handed and the other five were left-handed. On the basis of pitching maximum ball velocity during testing, the subjects with ball velocity greater than 0.5 SD above the mean (> 36.2 m·s^{-1}) were assigned to the high-velocity group, while the subjects with ball velocity lower than 0.5 SD below the mean (< 34.4 m·s^{-1}) were assigned to the low-velocity group. Therefore, a total of 20 subjects were assigned to either the high-velocity group (n = 10, HG) or the low-velocity group (n = 10, LG). The average ball velocity

Received: 03 April 2014 / Accepted: 25 June 2014 / Published (online): 01 December 2014

Table 1. Physical characteristics and ball velocity. Values are expressed as mean (± SD).

	Total (n =30)	High velocity group (n =10)	Low velocity group (n =10)	p	ES
Age (yr)	19.6 (.9)	19.3 (.7)	19.4 (.8)	.76	.14
Height (m)	177.4 (5.2)	177.8 (5.5)	177.9 (5.9)	.72	.17
Weight (kg)	73.9 (10.9)	75.4 (12.4)	77.8 (12.3)	.79	.12
Baseball career (yr)	11.2 (1.8)	11.4 (1.7)	10.7 (1.6)	.30	.49
Pitcher's career (yr)	7.6 (3.2)	8.1 (3.4)	6.0 (2.9)	.16	.67
Ball velocity ($m \cdot s^{-1}$)	35.3 (1.8)	37.4 (.8) *	33.3 (.8)	.00	5.01

P; p value, ES; effect size value. * Significant difference between high- and low-velocity groups ($p < 0.01$)

was significantly higher in the HG than in the LG (37.4 ± 0.8 $m \cdot s^{-1}$ vs. 33.3 ± 0.8 $m \cdot s^{-1}$). However, the physical characteristics did not differ significantly between the two groups. The Ethics Committee on Human Research of the National Institute of Fitness and Sports in Kanoya approved this study. All subjects provided written informed consent to participate in the study after being informed of its purpose and associated risks.

Experimental design

The participants threw a baseball from a portable pitching mound towards a strike zone marked on a home plate. The force plate was attached to the rigid steel frame of the portable pitching mound. The distance between the portable pitching mound and the home plate was the same as the official pitching distance (18.44 m). Ball velocity was measured using a radar gun (2ZM-1035, Mizuno Corporation, Tokyo, Japan) positioned behind the strike zone and adjusted to the position of the ball release. Prior to the pitching trials, participants performed warm-up exercises including stretching. After the completion of the warm-up exercises, the subjects were asked to perform fastball pitches 10 times at maximal effort with an interval of about 15 seconds between the trials.

Data collection

The GRF of the pivot and stride legs during pitching was measured using two multicomponent force plates (Z15907, 60 × 120 cm, Kistler Corporation, Winterthur, Switzerland), each of which had a sampling rate of 2000 Hz. Thirty-nine reflective markers aligned to specific body landmarks were attached directly onto the skin to minimize movement artifacts. Three-dimensional coordinates were measured using a motion analysis system (Eagle System, Motion Analysis Corporation, Santa Rosa, CA) with 12 Eagle cameras with a sampling rate of 500 Hz and a shutter speed of 2000 Hz. The root mean-square error in the calculation of the three-dimensional marker location was found to be less than 1.0 mm. The three-dimensional coordinates and the GRF were synchronized using software (Cortex 1.1.4.368, Motion Analysis Corporation, Santa Rosa, CA) and then calculated. Marker position data were filtered using a fourth-order Butterworth low-pass filter with a cut-off frequency of 13.4 Hz (Fleisig et al., 1999). The GRF and three-dimensional coordinates were defined as follows: Y-axis, throwing direction; Z-axis, vertical axis; X-axis, third-base direction, perpendicular to the Y- and Z-axes. The X-axis was reversed between right- and left-handers; the first-base direction for the left hander was defined as "+".

Data analysis

Kinematic and kinetic parameters were calculated with software (Motion musculous 1.51, Motion Analysis

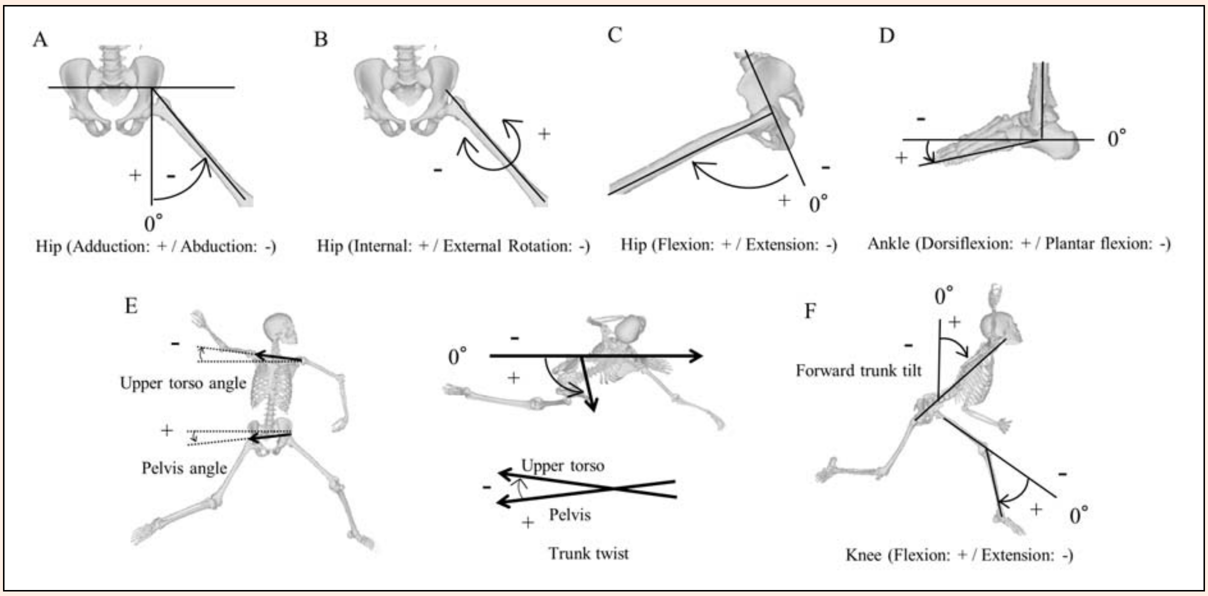


Figure 1. Definitions of kinematic variables. **(A)** Hip adduction/abduction, **(B)** hip (internal/external rotation), **(C)** hip (flexion/extension), **(D)** ankle (dorsiflexion/plantar flexion), **(E)** upper torso, pelvis angles and trunk twist, **(F)** forward trunk tilt and knee (flexion/extension).

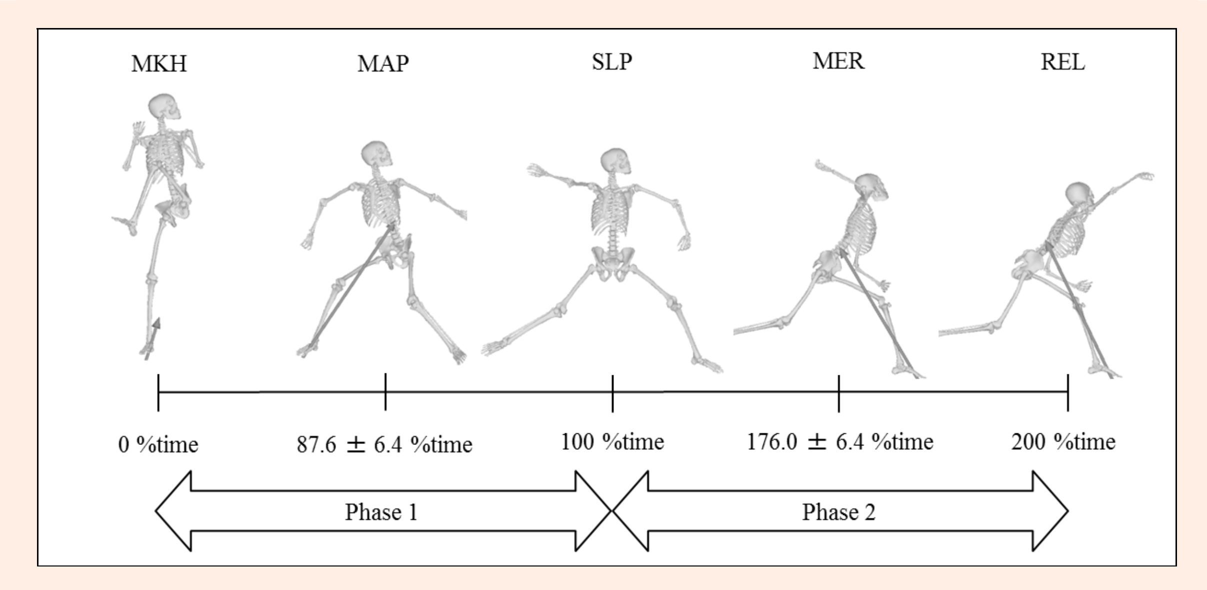


Figure 2. Phases of pitching motion. MKH; Maximal stride knee height. MAP; Maximal anterior push-off force. SFC; Stride foot contacts ground. MER; Maximum shoulder external rotation. REL; Ball release. Values measured from MKH until a particular event, expressed in time (s) or percentage of phase 1 (where 0% corresponds to the instant of maximal height of the knee of the stride leg and 100% corresponds to the instant of stride foot contact) and phase 2 (where 100% corresponds to the instant of stride foot contact and 200% corresponds to the instant of ball release).

Corporation, Santa Rosa, CA), utilizing the inverse-dynamics computation of musculoskeletal human models using motion-capture data (Nakamura et al., 2005). Kinematic parameters were calculated using the same methods as previously described elsewhere (Fleisig et al., 1996; Ishida and Hirano, 2004; Milewski et al., 2012; Stodden et al., 2001). The joint angles in the lower extremities were calculated using Euler equations of motion. Hip motion (coronal, sagittal, and transverse planes) and knee motion (sagittal plane) were calculated for both pivot and stride legs using standard angle definitions (Milewski et al., 2012; Figure 1 A-D, F). Stride length was measured and defined as the distance between the ankle joint centers at foot contact, expressed as a percentage of the subject's height. Pelvis orientation was defined as the angle between a line connecting the two anterior superior iliac spine markers and the Y-axis in the XY plane (Stodden et al., 2001; Figure 1E). The upper torso orientation was defined as the angle between a line connecting the shoulder markers and the Y-axis in the XY plane (Stodden et al., 2001; Figure 1E). The pelvis and upper torso orientation angle was positive when they were "open" (i.e., their anterior aspect visible to the batter) and negative when they were "closed" (their posterior aspect visible to the batter) (Ishida and Hirano, 2004; Stodden et al., 2001; Figure 1E). Transverse plane rotation of the pelvis and upper torso orientation were measured with respect to the Y-axis (home plate). The pelvis and upper torso angle were at 90° of transverse rotation when they were square to the home plate. When the right and left anterior superior iliac spines were parallel to the home plate, the pelvic rotation equaled 90°. Trunk twist angle was defined as the difference between the pelvis and the upper torso angles (Ishida and Hirano, 2004; Figure 1E). Forward trunk tilt was the angle between the superior direction of the trunk and global Y (in the throwing direction) in the global YZ plane (Figure 1F). Forward trunk tilt was therefore 90° when the trunk was horizontal toward the target and 0° when the trunk was vertical (Fleisig et al., 1996; Matsuo et al., 2001; Stodden et al., 2001). For each displacement measurement, the corresponding velocity was calculated using the 5-point central difference method (Miller and Nelson, 1973). The joint torque was calculated at the hip, knee, and ankle using kinematic data, and inverse dynamics equations (Nakamura et al., 2005). To eliminate any effects of variation in body size, kinetic and GRF data were normalized as divided by body weight.

To simplify interpretation of the results, throwing motion was divided into six phases (Figure 2) as previously defined for baseball pitching: windup, stride, arm cocking, arm acceleration, arm deceleration, and follow-through (Fleisig et al., 1996; 1999; Stodden et al., 2001). The position during pitching define the points in time when the knee of the stride leg reached maximal height (MKH), the stride foot made contact with the ground (SFC), the shoulder joint reached maximal external rotation (MER), and the ball was released (REL). In addition, we added the time of maximal anterior (Y: toward the throwing direction) push-off forces (MAP) as described by Mac Williams et al. (1998). Ground contact was defined by the resultant force of the stride leg that was greater than 50 N. Data was analyzed from two phases in the present study. These two phases were defined as from MKH to SFC (phase 1), and from SFC to REL (phase 2). The GRF on the pivot leg was mainly measured in the phase 1, whereas that on the stride leg was measured in the phase 2. The GRF on the pivot leg was measured after SFC but its magnitude was small. Therefore, the GRF on the pivot leg in the phase 2 was not analyzed. The GRF on the stride leg was not measured because the stride foot was in the air until SFC. Temporal data were calculated, with the time of MKH defined as 0%, the time of SLP defined as 100%, and the time of REL defined as 200%. The angles of the trunk and lower legs were measured at five instances: MKH, MAP, SFC, MER, and REL.

Table 2. Lower-limb kinematics and temporal parameters. Values are expressed as mean (± SD).

Variable	High velocity group (n =10)	Low velocity group (n =10)	p	ES	High velocity Group (n =10)	Low velocity group (n =10)	p	ES
Phase time/Strength length								
Phase 1 time (s)	.9 (.2)	.9 (.2)	.80	.11				
Phase 2 time (s)	.2 (.0)	.2 (.0)	.30	.48				
Total Pitch Time (s)	1.0 (.2)	1.1 (.2)	.76	.14				
Stride length (m)	1.5 (.1)	1.5 (.1)	.81	.11				
Stride length (%height)	85.0 (3.7)	85.2 (4.1)	.91	.11				
Angles		**Pivot leg**				**Stride leg**		
Hip coronal plane (Adduction: +; Abduction: -)								
Angle at MKH (°)	-24.8 (6.9)	-26.9 (5.6)	.48	.32	19.7 (15.3)	19.4 (7.2)	.97	.02
Angle at MAP (°)	-13.5 (10.5) *	-24.7 (8.3)	.02	1.12	-16.3 (11.6)	-27.8 (15.2)	.09	.81
Angle at SFC (°)	-40.0 (4.7) *	-45.2 (4.8)	.03	1.05	-37.1 (5.4)	-40.9 (5.5)	.15	.67
Angle at MER (°)					29.3 (16.8)	21.8 (16.5)	.35	.43
Angle at REL (°)					37.8 (13.1)	29.9 (9.8)	.17	.64
Hip transverse plane (Internal rotation: +; External rotation: -)								
Angle at MKH (°)	-24.4 (8.7)	-25.5 (5.6)	.76	.14	-41.5 (13.9)	-38.7 (11.8)	.66	.20
Angle at MAP (°)	-32.3 (7.4)	-31.8 (9.7)	.91	.05	-36.8 (7.8)	-36.6 (6.6)	.95	.03
Angle at SFC (°)	-27.1 (7.9)	-29.0 (9.2)	.65	.21	-47.5 (6.5)	-46.9 (7.9)	.85	.09
Angle at MER (°)					-23.3 (7.4)	-21.7 (6.0)	.61	.23
Angle at REL (°)					-15.3 (6.8)	-17.7 (6.7)	.45	.35
Hip sagittal plane (Flexion: +; Extension: -)								
Angle at MKH (°)	13.9 (4.7)	16.7 (6.1)	.30	.48	112.3 (6.6)	105.9 (7.0)	.06	.89
Angle at MAP (°)	62.5 (7.8)	58.3 (9.8)	.33	.45	48.2 (14.9)	40.6 (12.9)	.26	.52
Angle at SFC (°)	24.5 (11.3)	26.5 (14.6)	.74	.15	63.4 (12.4)	60.5 (10.4)	.61	.23
Angle at MER (°)					110.7 (10.8)	105.1 (5.0)	.18	.63
Angle at REL (°)					105.3 (12.7)	100.4 (6.2)	.32	.46
Knee sagittal plane (Flexion: +; Extension: -)								
Angle at MKH (°)	19.1 (8.2)	16.5 (5.3)	.43	.36	114.5 (17.9)	110.6 (12.1)	.59	.24
Angle at MAP (°)	49.4 (10.1)	47.9 (7.4)	.73	.16	33.7 (17.5)	37.2 (8.3)	.59	.25
Angle at SFC (°)	25.5 (6.4)	26.4 (9.7)	.82	.10	46.0 (6.7)	44.2 (8.0)	.95	.03
Angle at MER (°)					39.5 (13.1)	44.7 (10.2)	.36	.42
Angle at REL (°)					27.5 (13.4) *	42.1 (12.8)	.03	1.05
Ankle sagittal plane (Dorsiflexion: +; Plantarflexion: -)								
Angle at MKH (°)	-1.9 (5.7) *	5.2 (6.7)	.03	1.09	8.2 (17.7)	8.3 (13.9)	.99	.00
Angle at MAP (°)	1.3 (7.4)	-.4 (9.4)	.67	.20	12.1 (10.5)	11.9 (14.1)	.96	.02
Angle at SFC (°)	37.0 (9.0)	28.8 (10.3)	.09	.81	17.8 (11.2)	20.1 (17.9)	.75	.15
Angle at MER (°)					21.6 (5.3)	21.1 (5.8)	.84	.09
Angle at REL (°)					23.9 (6.5)	21.7 (6.3)	.49	.32
Joint angular velocities(°·s^{-1})								
Max Hip Add AV	132.4 (52.0)	148.2 (34.0)	.45	.34	860.8 (179.8)	781.5 (116.6)	.28	.49
Max Hip Abd AV	306.5 (74.4)	262.7 (71.2)	.22	.58	49.6 (137.5)	9.7 (84.3)	.28	.52
Max Hip IntR AV	144.5 (76.2)	167.5 (162.5)	.71	.17	528.5 (102.5)	428.2 (114.6)	.07	.85
Max Hip ExtR	65.5 (20.4)	79.7 (29.9)	.26	.51	70.1 (77.4)	81.6 (58.9)	.72	.16
Max Hip Flexion AV	153.6 (26.6)	141.8 (48.8)	.53	.27	620.8 (110.0)	596.2 (123.6)	.66	.20
Max Hip Extension AV	549.7 (66.7)	541.5 (163.6)	.89	.06	209.2 (98.3)	182.8 (104.8)	.60	.27
Max Knee Extension AV	246.2 (80.5)	231.4 (53.8)	.65	.20	267.2 (98.6) *	163.6 (129.2)	.03	.84
Knee Extension AV at MER					-192.6 (137.3) *	-33.6 (123.7)	.02	1.15
Knee Extension AV at REL					-204.8 (100.0) *	-87.1 (101.0)	.04	1.11
Joint angular velocity temporal parameters (%time)								
Maximum Hip Add AV	65.9 (24.5)	60.2 (21.4)	.61	.25	150.8 (5.0)	154.1 (10.1)	.40	.40
Maximum Hip Abd AV	93.2 (3.9)	91.7 (3.8)	.39	.42	169.8 (45.7)	179.2 (39.7)	.65	.21
Maximum Hip IntR AV	91.6 (18.6)	85.3 (28.2)	.58	.25	165.0 (4.3)	162.1 (5.2)	.22	.60
Maximum Hip ExtR AV	67.4 (20.7)	80.6 (12.5)	.12	.75	138.8 (40.4)	137.8 (41.0)	.96	.02
Maximum Hip Flexion AV	43.1 (21.3)	48.8 (17.9)	.55	.27	129.0 (13.2)	126.6 (14.6)	.71	.16
Maximum Hip Extension AV	99.2 (1.2)	99.3 (0.9)	.86	.08	189.3 (4.8)	192.9 (2.8)	.07	.86
Maximum Knee Extension AV	90.0 (3.1)	93.4 (3.0)	.03	1.03	171.3 (23.6)	155.8 (38.5)	.32	.46

P; p value, ES; effect size value. MKH; Maximal stride knee height. MAP; Maximal anterior push-off force. SFC; Stride foot contacts ground. Max: maximum. Abd: abduction. Add: Adduction. AV: Angular Velocity. IntR: Internal Rotation. ExtR: External Rotation. MER; Maximum shoulder external rotation. REL; Ball release. * $p < 0.05$, Significant difference between high and low groups. ** $p < 0.01$, Significant difference between high and low groups

Table 3. Trunk kinematics and temporal parameter data. Values are expressed as mean (± SD).

Variable	High velocity group (n =10)	Low velocity group (n =10)	p	ES
Angles				
Upper Torso				
Angle at MKH (°)	-23.2 (17.2)	-17.6 (13.1)	.45	.35
Angle at MAP (°)	-30.4 (4.3)	-30.6 (13.9)	.97	.02
Angle at SFC (°)	-34.1 (7.3)	-28.6 (9.5)	.19	.61
Angle at MER (°)	82.6 (6.2)	82.3 (10.2)	.94	.04
Angle at REL (°)	124.0 (6.6) **	115.4 (5.3)	.01	1.36
Pelvis				
Angle at MKH (°)	-32.9 (20.4)	-30.5 (17.6)	.80	.12
Angle at MAP (°)	-21.3 (13.1)	-15.4 (7.7)	.26	.52
Angle at SFC (°)	15.7 (8.1)	15.7 (7.8)	.99	.00
Angle at MER (°)	93.8 (5.8)	88.6 (8.9)	.16	.66
Angle at REL (°)	102.8 (5.3)	96.3 (8.6)	.07	.86
Trunk twist				
Angle at MKH (°)	9.7 (10.0)	13.0 (7.3)	.44	.35
Angle at MAP (°)	-9.2 (12.3)	-15.2 (14.2)	.35	.43
Angle at SFC (°)	-49.8 (11.2)	-44.3 (9.3)	.27	.50
Angle at MER (°)	-11.2 (6.7)	-6.3 (10.9)	.27	.51
Angle at REL (°)	21.2 (6.9)	19.0 (6.7)	.52	.30
Forward trunk tilt				
Angle at MKH (°)	-3.0 (4.0)	-4.1 (5.5)	.62	.23
Angle at MAP (°)	-16.7 (4.2) *	-12.0 (4.3)	.03	1.05
Angle at SFC (°)	-3.1 (5.2)	-4.3 (3.9)	.58	.25
Angle at MER (°)	15.9 (6.1) *	9.2 (7.4)	.05	.93
Angle at REL (°)	28.4 (6.9) *	19.4 (7.8)	.02	1.16
Angular velocities				
Maximum Upper Torso Angular Velocity ($°\cdot s^{-1}$)	1360.8 (106.8) **	1120.2 (120.7)	.00	1.94
Maximum Pelvis Angular Velocity ($°\cdot s^{-1}$)	738.2 (72.8) *	638.8 (113.1)	.04	.99
Maximum Trunk Positive Twist Angular Velocity ($°\cdot s^{-1}$)	954.8 (127.8) **	764.2 (119.6)	.00	1.43
Maximum Trunk Negative Twist Angular Velocity ($°\cdot s^{-1}$)	462.1 (76.1) *	363.7 (117.8)	.05	.94
Maximum Forward Trunk Tilt Angular Velocity ($°\cdot s^{-1}$)	338.2 (42.8)	307.7 (63.1)	.24	.64
Upper Torso Angular velocity at MER ($°\cdot s^{-1}$)	1320.8 (112.4) **	1006.5 (198.5)	.00	1.85
Trunk twist Angular velocity at MER ($°\cdot s^{-1}$)	929.3 (131.3) **	694.6 (118.1)	.00	1.78
Forward Trunk Tilt Angular velocity at SFC ($°\cdot s^{-1}$)	121.2 (40.4) *	73.4 (36.7)	.02	1.17
Angular velocity temporal parameters				
Maximum Upper Torso Angular Velocity (%time)	168.6 (6.4)	166.8 (11.7)	.69	.18
Maximum Pelvis Angular Velocity (%time)	138.9 (10.7)	138.3 (11.6)	.91	.05
Maximum Trunk Positive Twist Angular Velocity (%time)	178.9 (2.4)	181.2 (6.1)	.31	.66
Maximum Trunk Negative Twist Angular Velocity (%time)	79.9 (4.9)	79.4 (4.1)	.82	.10
Maximum Forward Trunk Tilt Angular Velocity (%time)	191.7 (9.8)	193.2 (6.3)	.71	.17

P; p value, ES; effect size value. MKH; Maximal stride knee height. MAP; Maximal anterior push-off force. SFC; Stride foot contacts ground. MER; Maximum shoulder external rotation. REL; Ball release. * $p < 0.05$, Significant difference between high and low groups. ** $p < 0.01$, Significant difference between high and low groups.

Statistical analysis

Descriptive data are presented as means ± SDs. A two-way repeated measures ANOVA (group ×time) was used to test the effects of group and time and their interaction on the kinematics and kinetics parameters. When a significant interaction was found, an unpaired Student's t-test with a Bonferroni correction was used to test the difference in the measured variables between the HG and LG. In addition, the effect size (Cohen's d) was calculated to express the magnitude of the difference between the two means. The significance level was set at $p < 0.05$. All data were analyzed using SPSS Statistics 19 software (IBM Corporation, Chicago, IL).

Results

There were no significant differences between the HG and the LG in the duration of each pitching phase and stride length.

Table 2 shows descriptive data on the lower limb kinematics and temporal parameters. Pivot hip abduction angles at MER and SFC were significantly smaller in the HG than in the LG ($p < 0.05$). Stride knee extension angle at REL, stride knee extension angular velocity at MER and REL, and maximum stride knee extension angular velocity were significantly greater in the HG than in the LG ($p < 0.05$).

Table 3 shows a comparison between the two groups in terms of the trunk kinematics and temporal parameters. Upper trunk angle at REL and forward trunk tilt angles at MAP, MER, and REL were significantly greater in the HG than in the LG ($p < 0.05$). The maxima of the upper torso, pelvis, trunk positive twist and trunk negative twist angular velocities, upper torso and trunk twist angular velocities at MER, and forward trunk tilt angular velocity at SFC were significantly greater in the HG than in the LG ($p < 0.05$).

Table 4. GRF data and temporal parameters. Values are expressed as mean (± SD).

Variable	High velocity group (n =10)	Low velocity group (n =10)	p	ES	High velocity group (n =10)	Low velocity group (n =10)	p	ES
		Pivot leg				Stride leg		
	MKH				*MER*			
Force Fx (N/kg)	-.5 (.4)	-.2 (.2)	.08	.83	.8 (.8) *	-.2 (.9)	.02	1.10
Force Fy (N/kg)	1.0 (.7)	.6 (.5)	.15	.66	-11.6 (1.7) **	-9.4 (1.3)	.01	1.42
Force Fz (N/kg)	6.0 (1.3)	7.2 (1.9)	.12	.74	19.4 (1.7) **	16.6 (1.4)	.00	1.69
Resultant forces (N/kg)	6.2 (1.1)	7.3 (1.9)	.13	.71	22.7 (2.1) **	19.1 (1.7)	.00	1.75
	MAP				*REL*			
Force Fx (N/kg)	-.6 (.6)	-.1 (.7)	.10	.76	1.2 (1.0)	1.0 (.7)	.60	.25
Force Fy (N/kg)	9.6 (1.6) **	7.2 (.9)	.00	1.75	-10.0 (1.7) *	-7.8 (1.5)	.01	1.28
Force Fz (N/kg)	11.7 (2.7)	10.0 (1.1)	.10	.76	19.1 (1.7) **	15.2 (1.9)	.00	1.98
Resultant forces (N/kg)	15.2 (2.9) *	12.4 (1.0)	.01	1.20	21.6 (2.2) **	17.1 (2.3)	.00	1.86
Maxima and minima of GRF (N/kg)								
Maximum Fx	1.5 (.5)	1.2 (.5)	.24	.53	1.7 (.7) *	1.0 (.6)	.05	.94
Maximum Fy	9.6 (1.6) **	7.2 (.9)	.00	1.75				
Maximum Fz	13.7 (2.1)	12.3 (1.1)	.10	.77	20.6 (1.7) **	17.5 (1.6)	.00	1.74
Maximum Resultant forces	16.2 (2.6) *	13.7 (1.1)	.01	1.23	23.7 (2.2) **	20.3 (2.2)	.00	1.44
Minimum Fx	-1.1 (.5) *	-0.6 (.3)	.01	1.22	-1.4 (.8)	-1.2 (.7)	.60	.24
Minimum Fy					-11.7 (1.6) *	-10.2 (1.7)	.05	.81
Maxima and minima of GRF temporal parameters (%time)								
Maximum Fx	97.0 (2.5)	83.8 (22.9)	.10	.83	173.2 (29.7)	190.0 (20.1)	.18	.67
Maximum Fy	83.6 (3.7)	87.0 (4.7)	.11	.74				
Maximum Fz	71.4 (9.8)	67.0 (8.3)	.31	.45	187.2 (7.6) *	178.6 (7.1)	.02	1.19
Maximum Resultant forces	73.0 (9.8)	70.9 (11.9)	.69	.17	185.5 (7.8) *	177.7 (6.4)	.03	1.12
Minimum Fx	60.3 (31.8)	43.7 (35.5)	.31	.48	133.1 (25.7)	121.8 (14.7)	.27	.50
Minimum Fy					177.5 (9.9)	170.0 (12.1)	.16	.64

P; p value, ES; effect size value. MKH; Maximal stride knee height. MAP; Maximal anterior push-off force. SFC; Stride foot contacts ground. MER; Maximum shoulder external rotation. REL; Ball release. * $p < 0.05$, Significant difference between high and low groups. ** $p < 0.01$, Significant difference between high and low groups.

Table 4 shows descriptive data on GRF data and temporal parameters. Fy on the pivot leg at MAP and Fx on the stride leg at MER were significantly greater in the HG than in the LG ($p < 0.05$). Fy, Fz, and resultant forces on the stride leg at MER and REL for the HG were significantly greater than those for the LG. The maxima of Fy and resultant forces and minima of Fx force on the pivot leg were significantly greater in the HG than in the LG ($p < 0.05$). The maxima of Fx, Fy, Fz, and resultant forces and minima of Fy force on the stride leg significantly greater in the HG than in the LG ($p < 0.05$). Maximum Fz and resultant forces on the stride leg occurred just prior to REL, with a significantly later occurrence in the HG than in the LG ($p < 0.05$).

Table 5 shows a comparison between the HG and the LG in terms of the joint torques of lower limbs and their temporal parameters. The joint torques of pivot hip abduction, pivot hip internal rotation, and pivot knee extension at MAP, and stride hip adduction at SFC were significantly greater in the HG than in the LG ($p < 0.05$). The maxima of pivot hip abduction, pivot hip internal rotation, pivot hip flexion, knee flexion, and pivot knee extension torques were significantly greater in the HG than in the LG ($p < 0.05$).

Discussion

The ball velocity for the HG (37.4 ± 0.8 m·s^{-1}) was higher than that reported previously for university baseball pitchers (33-35 m·s^{-1}, Felter and Dapena, 1986; Fleisig et al., 1999; Sakurai et al., 1993; Stodden et al., 2001) and almost the same as that for professional pitchers (Fleisig et al., 1999, 37.0 m·s^{-1}; Urbin et al., 2012, 37.2 m·s^{-1}) and elite pitchers (Dillman et al., 1993, 36.0 m·s^{-1}). Thus, the pitching ability of the HG can be considered to be comparable to those of professional and elite baseball pitchers who were examined in previous studies.

The maxima of Fy and resultant forces on the pivot leg were significantly greater in the HG than in the LG (Table 4). In addition, Fy and resultant forces on the pivot leg at MAP were significantly greater in the HG than in the LG (Table 4). Mac Williams et al. (1998) reported that the landing leg serves as an anchor in transforming the forward and vertical momentum into rotational components; posteriorly directed forces at the landing foot reflect an overall balance of the inertial forces of the body moving forward to create ball velocities because the maxima of GRF (Fy, Fz, and resultant forces) on the pivot leg and Fz and Fy at MAP were highly correlated with wrist velocity at the time of ball release. The current results support this finding and indicate that the pitcher with high pitched ball velocity can generate the inertial forces for moving the body forward before stride foot contact.

In the pivot leg, joint torques during hip abduction, hip internal rotation, and knee extension were significantly greater in the HG than in the LG (Table 5). Campbell et al. (2010) reported that the gastrocnemius, vastus medialis, gluteus maximus, and biceps femoris of the pivot leg elicited average muscle activity levels of 75, 68, 73, and 48% of their respective maximal voluntary isometric contractions from stride knee peak flexion to stride foot contact, which promoted concentric plantar

Table 5. Lower-limb joint torques and temporal parameters. Values are expressed as mean (± SD).

Variable	High velocity group (n =10)	Low velocity group (n =10)	p	ES	High velocity group (n =10)	Low velocity group (n =10)	p	ES
Joint torques (Nm/kg)		Pivot leg				Stride leg		
Hip Coronal Plane (Adduction: +; Abduction: -)								
Joint torque at MKH	-.2 (.3)	-.4 (.2)	.08	.84	-.1 (.1)	-.1 (.0)	.87	.07
Joint torque at MAP	-2.5 (.7) **	-1.3 (.8)	.00	1.53	.0 (.3)	.2 (.3)	.06	.89
Joint torque at SFC	-.3 (1.1)	.7 (.9)	.05	.92	1.2 (.2) *	.8 (.4)	.04	1.01
Joint torque at MER					-1.8 (.4)	-1.6 (.7)	.38	.42
Joint torque at REL					-2.1 (.4)	-1.8 (.4)	.12	.76
Hip Transverse Plane (Internal Rotation: +; External Rotation: -)								
Joint torque at MKH	-.1 (.2)	.0 (.1)	.20	.59	.0 (.1)	.1 (.0)	.19	.60
Joint torque at MAP	1.2 (.6) **	.4 (.5)	.01	1.30	.0 (.1)	-.1 (.1)	.14	.70
Joint torque at SFC	-.1 (.4)	-.2 (.2)	.33	.45	-.3 (.1)	-.3 (.2)	.82	.10
Joint torque at MER					.5 (.3)	.4 (.4)	.42	.37
Joint torque at REL					.5 (.5)	.6 (.3)	.58	.25
Hip Sagittal Plane (Flexion: +; Extension: -)								
Joint torque at MKH	.6 (.8) *	-.1 (.5)	.05	.93	-.1 (.4)	.2 (.1)	.07	.86
Joint torque at MAP	.0 (.9)	-.8 (1.1)	.10	.77	.2 (.2)	.2 (.4)	.99	.00
Joint torque at SFC	-.7 (.3)	-1.1 (.8)	.23	.55	.0 (.3)	-.2 (.4)	.32	.46
Joint torque at MER					-2.5 (.8)	-2.1 (.7)	.36	.42
Joint torque at REL					-2.5 (.9)	-2.0 (.7)	.23	.55
Knee Sagittal Plane (Flexion: +; Extension: -)								
Joint torque at MKH	-.6 (.5) *	-.1 (.3)	.02	1.10	.0 (.2)	.0 (.1)	.95	.03
Joint torque at MAP	-2.1 (.7) *	-1.4 (.6)	.03	1.02	.1 (.1)	.1 (.1)	.77	.13
Joint torque at SFC	.5 (.3)	.3 (.4)	.34	.44	-.2 (.3)	-.1 (.2)	.30	.49
Joint torque at MER					-1.4 (.7)	-1.5 (.6)	.67	.19
Joint torque at REL					-.6 (1.3)	-1.2 (.8)	.23	.56
Ankle Sagittal Plane (Dorsiflexion: +; Plantar flexion: -)								
Joint torque at MKH	.2 (.2)	.4 (.2)	.08	.84	.0 (.0)	.0 (.0)	.34	.44
Joint torque at MAP	1.1 (.3)	.9 (.5)	.35	.43	.0 (.0)	.0 (.0)	.26	.52
Joint torque at SFC	.3 (.3)	.4 (.4)	.34	.44	-.1 (.0)	.0 (.0)	.11	.76
Joint torque at MER					.9 (.7)	.6 (.4)	.35	.43
Joint torque at REL					.9 (.6)	.5 (.4)	.15	.67
Maximum joint torque (Nm/kg)								
Maximum Hip Adduction	.6 (.8)	.9 (.9)	.75	.34	1.1 (.2)	.8 (.4)	.17	.85
Maximum Hip Abduction	2.9 (.7) *	2.1 (.6)	.05	1.14	2.3 (.4)	1.9 (.5)	.09	.93
Maximum Hip IntR	1.3 (.5) *	.7 (.4)	.02	1.27	.6 (.3)	.7 (.3)	.45	.09
Maximum Hip ExtR	.3 (.3)	.3 (.3)	.38	.04	.3 (.1)	.4 (.2)	.22	.41
Maximum Hip Flexion	1.1 (.9)	0.4 (.9)	.08	.82	.0 (.3)	-.2 (.4)	.30	.52
Maximum Hip Extension	1.5 (.6)	1.4 (.8)	.72	.11	2.7 (.9)	2.3 (.6)	.42	.50
Maximum Knee Flexion	.7 (.4)	.4 (.3)	.09	.79	.1 (.6)	.1 (.2)	.59	.12
Maximum Knee Extension	2.7 (.5) *	1.9 (.4)	.02	1.44	1.9 (.6)	1.8 (.4)	.83	.36
Maximum Ankle DF	1.2 (.3)	1.1 (.4)	.47	.43	1.0 (.6)	.8 (.4)	.18	.43
Maximum joint torque temporal parameters (%time)								
Maximum Hip Adduction	70.7 (41.7)	99.1 (1.5)	.12	.91	101.4 (4.3)	106.5 (12.7)	.27	.51
Maximum Hip Abduction	71.9 (16.8)	67.5 (11.2)	.92	.29	192.9 (6.0)	192.5 (7.6)	.87	.05
Maximum Hip IntR	76.4 (7.7)	69.9 (7.6)	.18	.81	181.6 (18.5)	182.4 (18.4)	.54	.04
Maximum Hip ExtR	80.3 (35.4)	81.7 (35.0)	.90	.04	110.0 (30.0)	114.1 (14.9)	.71	.17
Maximum Hip Flexion	46.9 (31.7)	40.5 (27.7)	.87	.20	104.3 (5.1)	101.7 (3.7)	.21	.56
Maximum Hip Extension	96.8 (2.4)	95.3 (2.1)	.47	.62	181.6 (10.7)	171.4 (17.6)	.16	.67
Maximum Knee Flexion	89.8 (26.6)	84.5 (29.2)	.95	.18	130.0 (45.8)	125.2 (38.2)	.42	.11
Maximum Knee Extension	72.1 (9.7)	74.1 (8.1)	.55	.22	157.3 (14.5)	170.2 (17.4)	.06	.77
Maximum Ankle DF	86.6 (6.5)	68.6 (33.4)	.14	.71	178.8 (31.5)	158.8 (31.3)	.38	.60

P; p value, ES; effect size value. MKH; Maximal stride knee height. MAP; Maximal anterior push-off force. SFC; Stride foot contacts ground. IntR: Internal Rotation. ExtR: External Rotation. DF: Dorsiflexion. MER; Maximum shoulder external rotation. REL; Ball release. * $p < 0.05$, Significant difference between high and low groups. ** $p < 0.01$, Significant difference between high and low groups

flexion, knee extension, and hip extension. In the current results, the ankle joint torque was similar between the two groups.

Taking current results into account together with the report of Campbell et al. (2010), it is likely that as compared to low-ball-velocity pitchers, high-ball-velocity pitchers can generate greater momentum by hip extension/abduction and knee extension in the pivot leg for accelerating the body forward.

During the arm acceleration phase (from MER to REL), the HG extended their stride knee with greater angular velocity and greater range of motion than the LG (Table 2). In addition, the HG increased maximum pelvis, upper torso, and trunk twist angular velocities during phase 2 and forward trunk tilt angle at MER and REL than LG (Table 3). High-ball-velocity pitchers have been observed to exhibit greater stride knee extension (Matsuo et al., 2001), trunk rotation (Fleisig et al., 1999; Matsuo et al., 2001; Stodden et al., 2001), and forward trunk tilt (Matsuo et al., 2001). Concomitant with knee extension, the trunk rotates forward (Escamilla et al., 1998). Taking these findings into account together with the current results, it may be assumed that a pitcher with high pitched ball velocity can increase the rotation and forward motion of the trunk by stride knee extension during the arm acceleration phase.

The maxima of Fx, Fz, and resultant forces and minima of Fy force on the stride leg were significantly greater in the HG than in the LG (Table 4). Furthermore, GRF at MER and REL were also significantly greater in the HG than in the LG (Table 4). Maximum Fz and resultant forces on the stride leg occurred just prior to REL, occurring significantly later in the HG than in the LG (Table 4). The energy of the lower limbs during pitching is transferred to the trunk and arms (Elliott et al., 1988; Matsuo et al., 2001; Stodden et al., 2001; Williams et al., 1998). Elliott et al. (1988) suggested that the ability to drive the body over a stabilized stride leg was a characteristic of high-ball-velocity pitchers. Mac Williams et al. (1998) reported that the maxima of GRF (Fy, Fz, and resultant forces) on stride legs and Fy, Fz, and resultant forces at REL correlated highly with wrist velocity at the time of ball release. The current results support these findings and suggest that high-ball-velocity pitchers can generate greater inertial forces until ball release, which cause the upper body to move forward, and create high-pitched ball velocity.

Hip adduction torque on the stride leg at SFC was significantly greater in the HG than in the LG (Table 5). Campbell et al. (2010) reported that the high activation levels of the vastus medialis in the stride leg during the arm acceleration phase explain its important roles in controlling/stabilizing knee joint positions, while the upper extremity and torso forcefully rotate about the stride hip. Taking this into account, it is likely that the hip adduction torque of the stride at SFC is important to control/stabilize the stride leg in order to increase the rotation and forward motion of the trunk during phase 2. If so, greater hip adduction torque on the stride leg at SFC for the HG may be assumed to be a factor for producing greater GRF (in the throwing direction and vertically) and knee extension on the stride leg as compared to the LG. For the pitcher with low-pitched ball velocity, it is important that they generate greater momentum at SFC by hip adduction of stride leg.

Although high levels of lower-limb strength are necessary in pitching, the fact that pitchers throwing at high velocity generated greater momentum of the lower limbs during pitching motion indicates that improvements in dynamic muscular strength/power may be important for increasing ball velocity. Weakness in the knee and hip has been implicated as a potential area for a break in the open kinetic chain in the pitching cycle (Burkhart et al., 2003). Thus, it seems that in addition to a small momentum of the lower limbs, low-ball-velocity pitchers cannot perform properly the open kinetic chain which transfers the energy of the lower limbs during pitching to the trunk and arms. In this sense, the computation of the lower-extremity kinetics and measurement of lower-extremity strength may help clarify the role of muscle strength in determining knee and hip function in baseball pitching.

Conclusion

The current results indicate that high-ball-velocity pitchers are characterized by greater momentum of the lower limbs during pitching motion. The present study suggests that such pitchers can generate greater maxima of hip and knee torques in the pivot leg in order to increase the inertial forces of the body moving forward, and they can increase hip adduction torque of the stride at SFC, and exhibit greater GRF (in the throwing direction and vertically) and knee extension on the stride leg in order to increase the rotation and forward motion of the trunk during phase 2. Thus, the findings obtained here indicate that for high-pitched-ball velocity, stabilizing lower limbs during pitching plays an important role in order to increase the rotation and forward motion of the trunk.

Acknowledgements

This study was not funded. The authors would like to thank all individuals who participated in this study.

References

Atwater, A.E. (1979) Biomechanics of overarm throwing movements and of throwing injuries. *Exercise and Sport Sciences Reviews* **7,** 43-85.

Burkhart, S.S., Morgan, C.D. and Kibler, W.B. (2003) The disabled throwing shoulder: Spectrum of pathology part I: Patho anatomy and biomechanics. Arthroscopy: *The Journal of Arthroscopic & Related Surgery* **19(4),** 404-420.

Campbell, B.M., Stodden, D.F. and Nixon, M.K. (2010) Lower extremity muscle activation during baseball pitching. *Journal of Strength and Conditioning Research* **24(4),** 964-971.

Dillman, C.J., Fleisig, G.S. and Andrews, J.R. (1993) Biomechanics of pitching with emphasis upon shoulder kinematics. *The Journal of Orthopaedic and Sports Physical Therapy* **18(2),** 402-408.

Elliott, B., Grove, J.R. and Gibson, B. (1988) Timing of the lower limb drive and throwing limb movement in baseball pitching. *International Journal of Sport Biomechanics* **4,** 59-67.

Escamilla, R.F., Fleisig, G.S., Barrentine, S.W., Zheng, N. and Andrews, J.R. (1998) Kinematic comparisons of throwing different types of baseball pitches. *Journal of Applied Biomechanics* **14,** 1-23.

Felter, M. and Dapena, J. (1986) Dynamics of the shoulder and elbow joints of the throwing arm during a baseball pitch. *International Journal of Sport Biomechanics* **2(4),** 235-259.

Fleisig, G.S., Barrantine, S., Zheng, N., Escamilla, R. and Andrews, J. (1999) Kinematic and kinetic comparison of baseball pitching among various levels of development. *Journal of Biomechanics* **32(12),** 1371-1375.

Fleisig, G.S., Escamilla, R.F., Andrews, J.R. and Matsuo, T. (1996) Kinematic and Kinetic Comparison Between Baseball Pitching and Football Passing. *Journal of Applied Biomechanics* **12,** 207-224.

Ishida, K. and Hirano, Y. (2004) Effects of non-throwing arm on trunk and throwing arm movements in baseball pitching. *International Journal of Sport and Health Science* **2,** 119-128.

Kibler, W.B. (1991) Role of the scapula in the overhead throwing motion. *Contemporary Orthopaedics* **22,** 525-532.

Kibler, W.B. (1995) Specificity and sensitivity of the anterior slide test in throwing athletes with superior glenoid labral tears. Arthroscopy: *The Journal of Arthroscopic and Related Surgery* **11,** 296-300.

Kreighbaum, E. and Barthels, K.M. (1985) *Biomechanics - A qualitative approach for studying human movement 2nd ed*. Burgess, Minneapolis. 585-616.

MacWilliams, B.A., Choi, T., Perezous, M.K., Chao, E.Y. and McFar-

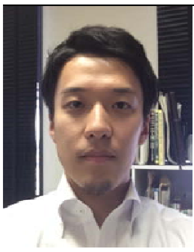
land, E.G. (1998) Characteristic ground-reaction forces in baseball pitching. *The American Journal of Sports Medicine* **26(1),** 66-71.
Matsuo, T., Escamilla, R.F., Fleisig, G.S., Barrentine, S.W. and Andrews, J.R. (2001). Comparison of kinematic and temporal parameters between different pitch velocity groups. *Journal of Applied Biomechanics* **17,** 1-13.
Miller, D.L. and Nelson, R.C. (1973) *Biomechanics of sport - A research approach*. Philadephia, Lee and Febiger.
Milewski, M.D., Ounpuu, S., Solomito, M., Westwell, M. and Nissen, C.W. (2012) Adolescent baseball pitching technique: lower extremity biomechanical analysis. *Journal of Applied Biomechanics* **28(5),** 491-501.
Myers, D. and Gola, M. (2000) *The Louisville Slugger complete book of pitching*. McGraw-Hill, New York.
Nakamura, Y., Yamane, K., Fujita, Y. and Suzuki, I. (2005) Somatosensory Computation for Man–Machine Interface From Motion-Capture Data and Musculoskeletal Human Model. *IEEE Transactions on Robotics* **21(1),** 58-66.
Robb, A.J., Fleisig, G., Wilk, K., Macrina, L., Bolt, B. and Pajaczkowski, J. (2010) Passive ranges of motion of the hips and their relationship with pitching biomechanics and ball velocity in professional baseball pitchers. *American Journal of Sports Medicine* **38,** 2487-2493.
Sakurai, S., Ikegami, Y., Okamoto, A., Yabe, K. and Toyoshima, S. (1993) A three-dimensional cinematographic analysis of upper limb movement during fastball and curveball baseball pitches. *Journal of Applied Biomechanics* **9,** 47-65.
Stodden, D.F., Fleisig, G.S., McLean, S.P., Lyman, S.L. and Andrews, J.R. (2001) Relationship of Pelvis and Upper Torso Kinematics to Pitched Baseball Velocity. *Journal of Applied Biomechanics* **17,** 164-172.
Urbin, M.A., Fleisig, G.S., Abebe, A. and Andrews, J.R. (2013) Associations between timing in the baseball pitch and shoulder kinetics, elbow kinetics, and ball speed. *American Journal of Sports Medicine* **41(2),** 336-342.

Key points

- High-ball-velocity pitchers are characterized by greater momentum of the lower limbs during pitching motion.
- For high-pitched-ball velocity, stabilizing lower limbs during pitching plays an important role in order to increase the rotation and forward motion of the trunk.
- Computation of the lower-extremity kinetics and measurement of lower-extremity strength may help clarify the role of muscle strength in determining knee and hip function in baseball pitching.

AUTHORS BIOGRAPHY

Masahiro KAGEYAMA
Employment
Graduate School of Physical Education, National Institute of Fitness and Sports in Kanoya
Degree
MSc
Research interests
Biomechanics
E-mail: m127003@sky.nifs-k.ac.jp



Takashi SUGIYAMA
Employment
Graduate School of Physical Education, National Institute of Fitness and Sports in Kanoya
Degree
MSc
Research interests
Biomechanics
E-mail: m127004@sky.nifs-k.ac.jp

Yohei TAKAI
Employment
National Institute of Fitness and Sports in Kanoya
Degree
PhD
Research interests
Exercise physiology, Aging, Growth and development
E-mail: y-takai@nifs-k.ac.jp

Hiroaki KANEHISA
Employment
National Institute of Fitness and Sports in Kanoya
Degree
PhD
Research interests
Exercise physiology
E-mail: hkane@nifs-k.ac.jp

Akira MAEDA
Employment
National Institute of Fitness and Sports in Kanoya
Degree
PhD
Research interests
Biomechanics
E-mail: amaeda@nifs-k.ac.jp

✉ **Akira Maeda**
National Institute of Fitness and Sports in Kanoya, 1 Shiromizu, Kanoya, Kagoshima 891-2393, Japan