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Three-dimensional kinematic analysis of throwing motion focusing on pelvic rotation at stride foot contact

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Background: Because the throwing motion can be considered a kinetic chain, pelvic and trunk motion should be included in the analysis. Early pelvic rotation during the throwing sequence has been reported to be a factor leading to overloading of the shoulder and the elbow. A large pelvic rotation angle at the stride foot contact (SFC) was thought to indicate early pelvic opening. This study examined the kinematic features in each motion segment associated with increased pelvic rotation at SFC in pitchers of various ages and competition levels.

Materials and methods: The study included 324 pitchers with various age/competition levels. Throwing motion was analyzed using an infrared-type motion capture system. In the assessment, pelvic rotation angle at SFC was adopted as a parameter for the timing of pelvic opening. Statistical analyses were performed for correlation between pelvic rotation and kinematic variables of other motion segments at the instant of SFC as well as the difference in kinematics between the groups of different levels.

Results: Most of the kinematic results were not significantly different among the 4 groups with different levels. The increase in the pelvic opening angle at SFC was significantly correlated with increased trunk bend to the nonthrowing arm side and decreased hip flexion angle on the throwing arm side.

Discussion and Conclusion: Early pelvic rotation in the throwing motion sequence, as manifested by increased pelvic rotation at SFC, was correlated with changes in kinematic parameters at other motion segments such as increased trunk tilt and decreased hip flexion.

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Throwing injuries in baseball pitchers present a substantial problem affecting the player's performance. Therefore, prevention and management of throwing injuries based on an accurate understanding of the injury mechanism is critically important.^{8,15,21,29,30} Numerous studies have investigated the factors related to the injury risk, including improper throwing mechanics, increased number of pitches and innings, throwing breaking balls, and fatigue.^{4,6,17}

Previous biomechanical studies of the kinematic and kinetic factors relevant to throwing injuries have indicated several pathologic mechanics leading to shoulder and elbow overload such as excessive horizontal shoulder abduction and insufficient elbow flexion.^{2,15,23} In addition to shoulder and elbow mechanics, throwing motion can be considered a kinetic chain, transmitting motion

and energy from the lower extremities to the upper limb.^{2,7,12} Therefore, analysis of pelvic and trunk motion is thought to also be important to understand the etiology of throwing injuries. Several studies have examined the effect of pelvic and trunk rotation on the upper extremity kinematics and kinetics.^{1,3,5,19,20,24,27}

Among the kinematic features of the pelvis and trunk in throwing motion, Fleisig et al.^{8,11} first addressed the significance of timing of the pelvic/trunk rotation, stating that early pelvic rotation during throwing could result in an increased load at the shoulder and elbow. Unfavorable kinematic chain sequence characterized by the too early pelvic rotation was represented as “opening up too soon” phenomenon by Meister et al.¹⁵ In previous studies, improper motion patterns in the trunk and the hip have also been analyzed as potential factors leading to overload at the shoulder and the elbow. Therefore, to prevent throwing injuries based on the concept of the kinematic chain, the relationship between the pelvic motion and kinematics of the other motion segments, such as upper trunk and upper extremities, should be included in the analysis.

In the “optimal” pitching motion sequence, the trunk rotation should be initiated around the timing of the stride foot contact (SFC).¹

The Nobuhara Hospital and Institute of Biomechanics Institutional Review Board approved this study (No. E156).

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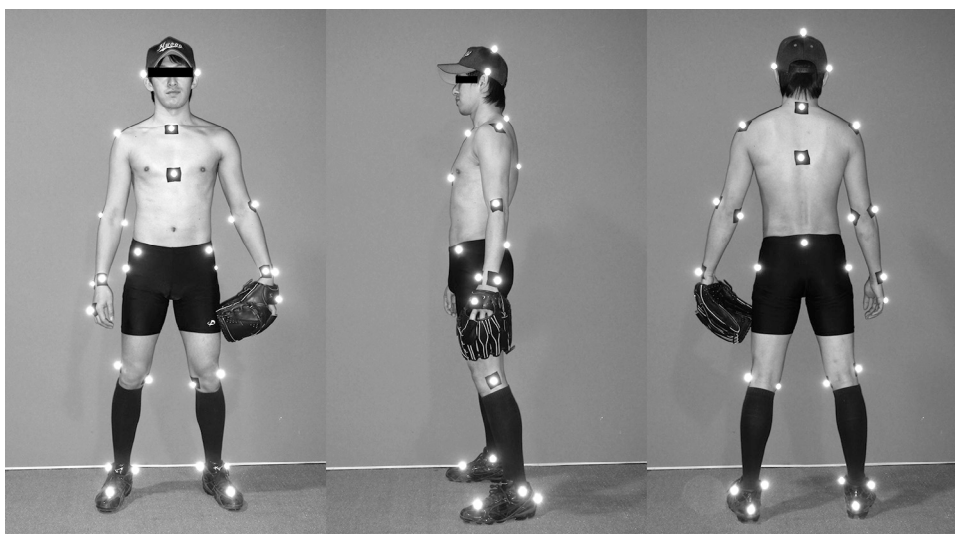


Figure 1 A total of 36 reflective plastic spheres were attached to the representative anatomic locations for the motion analysis.

Therefore, an increased pelvic rotation value in the transverse plane at the instant of SFC is thought to indicate the “opening up too soon” phenomenon.²⁷ In this study, we adopted the rotation angle of the pelvis at SFC as a parameter for the timing of pelvic rotation.

The purpose of this study was to examine the rotational kinematics and alignments of the trunk, the shoulder, and the hip (both lead and stance limbs) as well as the correlation between those kinematic results and increased pelvic rotation at SFC in pitchers of various ages and competition levels. The study hypotheses were as follows: first, there would be characteristic kinematic patterns in other motion segments, such as trunk and hip, which can be identified in association with early pelvic rotation at the SFC; and second, kinematic characteristics would be different among various ages/competition levels.

Materials and methods

Subjects

Motion analysis was performed for 324 pitchers with various competition levels. The study excluded pitchers who could not throw a fast ball due to shoulder or elbow pain. There were 146 youth-level pitchers (YP), 118 high school pitchers (HSP), 28 collegiate pitchers (CP), and 32 professional pitchers (PP). Age of the subjects ranged from 10 to 15 years in YP, 15 to 18 years in HP, and 18 years or older in CP and PP groups.⁹ Semiprofessional and professional pitchers were included in the PP group, and amateur-level pitchers older than 18 years were included in the CP group. The average and range values for age, height, body weight, and ball speed in each group are described in Table 1. All study participants read and signed a consent form before participation in this study.

Table 1

The average and range values for age, height, body weight, and ball speed in each group

Group	No.	Age (y)	Height (cm)	Weight (kg)	Ball speed (km/h)
Youth	146	13.4 ± 1.2	165.4 ± 9.7	55.8 ± 10.1	100.3 ± 9.7
High school	118	16.3 ± 0.7	174.5 ± 5.2	66.9 ± 6.9	112.9 ± 6.7
College	28	20.1 ± 1.4	177.1 ± 5.2	72.3 ± 6.7	119.1 ± 5.2
Professional	32	25.1 ± 4.2	179.8 ± 5.7	79.0 ± 8.7	121.2 ± 6.0

Data are presented as mean ± standard deviation.

Motion analysis system

Throwing motion was analyzed using an infrared-type motion capture system (ProReflex MCU-500+; Qualisys, Göteborg, Sweden). Seven charge-coupled device cameras were set up around the official regulation-size pitching mound. For motion analysis, 36 reflective plastic spheres were attached to the subjects' skin on the representative anatomic locations according to the method used in previous relevant studies.^{16,23} The location of each marker was determined by a physical therapist with adequate experience using this motion analysis system (Fig. 1).

The 3-dimensional (3D) positions of the markers during the motion were recorded at the rate of 500 Hz by the cameras. Ball speed was measured by a radar gun (SpeedMax2, Mizuno, Osaka, Japan). During the motion analysis, each subject was asked to throw a fastball at their maximum speed from the pitching mound to the home plate for a distance of 18.44 m (60'5") 3 times after a warm-up. The fastest pitch among the trials was considered to represent the “best” performance and used for the subsequent analysis^{16,23} (Fig. 2).



Figure 2 Three-dimensional positions of the markers during throwing motion were recorded by the charge-coupled device cameras.

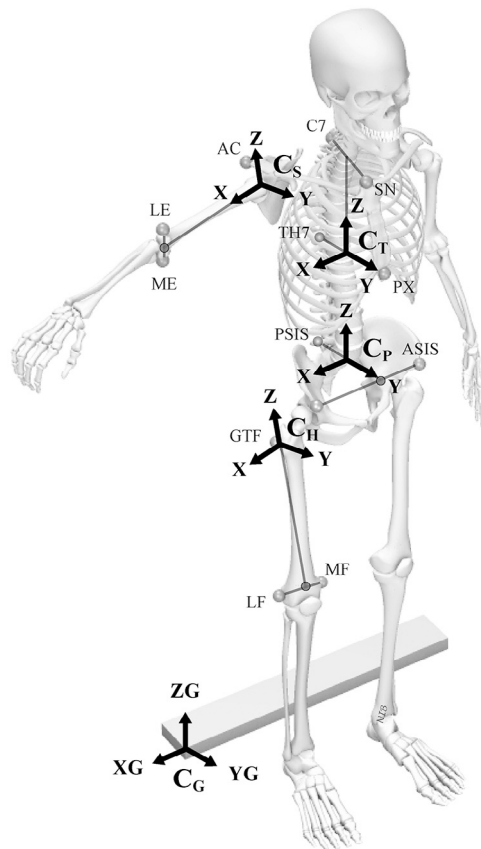


Figure 3 Coordinate system for each motion segment: C_G , global coordinate system; C_S , upper arm coordinate system; C_T , trunk coordinate system; C_P , pelvis coordinate system; C_H , hip coordinate system. X_G , X-axis of C_G ; Y_G , Y-axis of C_G ; Z_G , Z-axis of C_G ; C_7 , 7th cervical vertebra; SN , suprasternal notch; AC , acromion; LE , lateral epicondyle of the elbow; ME , medial epicondyle of the elbow; PX , xiphoid process; $Th7$, 7th thoracic vertebra; $PSIS$, the middle position of bilateral posterior superior iliac spine; GTF , great trochanter of the femur; LF , lateral epicondyle of the femur; MF , medial epicondyle of the femur.

Data analysis

In the data analysis, a rigid-body model was constructed, and the kinematic parameters were calculated based on the local coordinate system. The global coordinate system was established at the corner of the pitcher's plate on the mound. The X and Y axes (X_G and Y_G) were determined in reference to the line connecting the pitching rubber and the home plate (X_G), and the line connecting the left and right corners of the pitcher's plate (Y_G), respectively. The Z axis (Z_G) referred to the vertical axis. All 3D positions from the reflective markers were determined in reference to the global coordinate system. The coordinate system for each motion segment was defined mathematically based on the localization of the following representative anatomic landmarks: thigh, pelvis, trunk, upper arm, forearm, and hand (Fig. 3). These local coordinate systems were mathematically determined using a subset of 3D locations of the relevant markers. In the kinematic assessment for each motion segment, the 6-degrees-of-freedom motion was calculated using an Euler angle sequence. Pelvic motion was derived from the spatial relationship between the pelvic and the global coordinate systems.

Throwing motion was divided into the following 6 phases (1 to 6) by 5 time points (a to e): (1) wind-up, (2) stride, (3) arm cocking, (4) arm acceleration, (5) arm deceleration, and (6) follow-through for the phases; (a) knee highest position, (b) stride foot contact (SFC), (c) maximum external rotation of the shoulder, (d) ball release, and (e) maximum internal rotation of the shoulder for the time points.^{2,9,13,20,30} In the kinematic assessment, the motions of the pelvis (rotation in the transverse plane), hip (flexion/extension, abduction/adduction, and internal/external rotation), trunk (flexion/extension, side bend, and rotation), and shoulder (internal/external rotation, abduction/adduction, and horizontal abduction/adduction) at the instant of SFC were analyzed (Fig. 4). In the analysis of the kinematic data, pelvic rotation angle at SFC was used as the primary parameter.

Statistical analysis

The difference in the results among the groups was statistically analyzed using 1-way analysis of variance, and correlation analysis was performed based on the Pearson correlation coefficient. The significance level was set at $P < .05$. SPSS base version 15 software (IBM, Armonk, NY, USA) was used for the statistical analysis.

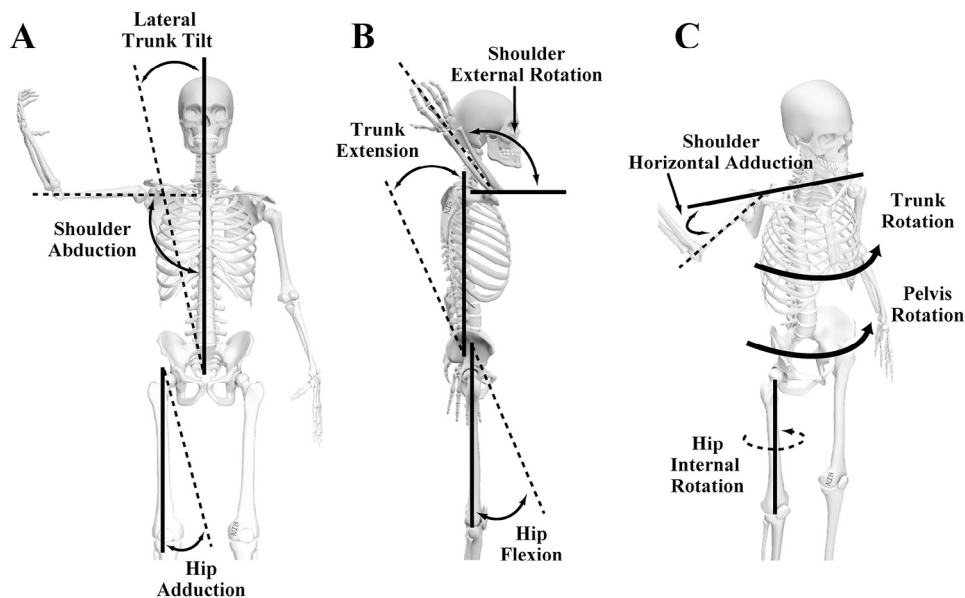


Figure 4 Definition of kinematics: (A) Lateral trunk tilt, shoulder abduction, and hip abduction; (B) shoulder external rotation, trunk extension, and hip flexion; (C) shoulder horizontal adduction, trunk and pelvis rotations, and hip internal rotation.

Results

Kinematic results

The average value of each kinematic variable at SFC is reported in [Table II](#) and stratified for the age/competition level. The average pelvic rotation angle at SFC in each group ranged from 42° to 48°. Except for the comparisons of trunk forward flexion and contralateral tilt between youth and adult players, no significant difference in the kinematic results was observed among the different level groups ([Table II](#)).

Correlation between pelvic rotation and other kinematic variables at SFC

Correlation between pelvic rotation and position/orientation of each motion segment at SFC is reported in [Table III](#). The pelvic rotation angle value at SFC was significantly correlated with increased trunk bend to the nonthrowing arm side (YP: $r = 0.63$, HSP: $r = 0.53$, CP: $r = 0.53$, PP: $r = 0.55$, with $P < .01$) and decreased hip flexion angle on the throwing arm side (YP: $r = 0.54$, HSP: $r = 0.65$, CP: $r = 0.78$, PP: $r = 0.62$, with $P < .01$) in all groups with different levels. In addition, increased adduction angle and decreased flexion angles of the hips on both sides were correlated with an increase in the pelvic rotation angle at SFC in the younger generation groups ($P < .001$), whereas increased shoulder external rotation was weakly correlated with pelvic rotation at SFC (YP: $r = 0.43$, HSP: $r = 0.43$, CP: $r = 0.44$, PP: $r = 0.38$, with $P < .05$).

Table II
The average value of each kinematic variable at stride foot contact

Parameter at SFC	Youth (mean ± SD)	High school (mean ± SD)	College (mean ± SD)	Professional (mean ± SD)	Significant differences among each level
Throwing side					
Hip adduction,°	-17.8 ± 10.9	-19.3 ± 10.0	-19.8 ± 12.3	-23.4 ± 9.8	n.s.
Hip internal rotation,°	4.0 ± 15.0	4.5 ± 2.7	8.4 ± 15.4	8.4 ± 13.6	n.s.
Hip flexion,°	-33.0 ± 8.3	-33.8 ± 7.8	-34.1 ± 15.4	-34.6 ± 9.7	n.s.
Nonthrowing side					
Hip adduction,°	-21.5 ± 20.7	-24.6 ± 22.8	-29.1 ± 16.9	-25.4 ± 16.6	n.s.
Hip internal rotation,°	0.4 ± 23.2	-0.4 ± 24.2	5.5 ± 19.1	-1.0 ± 19.1	n.s.
Hip flexion,°	55.4 ± 9.4	57.8 ± 6.9	58.9 ± 7.4	56.2 ± 8.1	n.s.
Pelvis right rotation,°	47.9 ± 13.0	45.6 ± 11.3	45.0 ± 12.6	42.0 ± 9.8	n.s.
Trunk forward tilt,°	10.1 ± 8.4	7.9 ± 10.9	6.7 ± 8.8	3.2 ± 12.2	a vs. d ($P = .002$)
Trunk contralateral tilt,°	6.6 ± 11.0	2.6 ± 10.5	1.0 ± 10.1	1.3 ± 10.2	a vs. b ($P = .02$)
Trunk rotation,°	-21.6 ± 9.5	-23.0 ± 9.4	-25.4 ± 12.8	-21.2 ± 10.5	n.s.
Shoulder external rotation,°	74.8 ± 25.8	74.3 ± 23.6	69.4 ± 31.0	68.9 ± 28.2	n.s.
Shoulder abduction,°	83.8 ± 12.9	85.2 ± 13.3	86.2 ± 12.7	85.4 ± 10.6	n.s.
Shoulder horizontal adduction°	-31.3 ± 13.4	-31.8 ± 13.5	-32.3 ± 14.6	-32.0 ± 11.9	n.s.

SFC, stride foot contact; SD, standard deviation; n.s., nonsignificant difference; a, youth; b, high school; d, professional.

Table III
Correlation between pelvic rotation and position/orientation of each motion segment at stride foot contact

Parameter at SFC	Youth		High school		College		Professional	
	r	P	r	P	r	P	r	P
Throwing side								
Hip adduction,°	0.32	<.001	0.42	<.001	0.42	.03	0.30	.09
Hip internal rotation,°	-0.25	<.001	-0.14	.12	0.04	.83	-0.20	.28
Hip flexion,°	-0.54	<.001	-0.65	<.001	-0.78	<.001	-0.62	<.001
Nonthrowing side								
Hip adduction,°	0.57	<.001	0.43	<.001	0.20	.32	0.15	.40
Hip internal rotation,°	-0.35	<.001	-0.23	.01	0.29	.12	0.08	.65
Hip flexion,°	0.34	<.001	0.13	.15	0.07	.72	0.10	.56
Trunk forward tilt,°	0.21	.01	0.14	.12	-0.07	.73	-0.22	.23
Trunk contralateral tilt,°	0.63	<.001	0.53	<.001	0.53	.004	0.55	.001
Trunk rotation,°	0.05	.56	0.13	.16	0.24	.22	0.21	.02
Shoulder external rotation,°	0.43	<.001	0.43	<.001	0.44	.02	0.38	.03
Shoulder abduction,°	0.08	.35	-0.15	.12	0.09	.65	-0.10	.63
Shoulder horizontal adduction,°	0.05	.52	-0.03	.70	-0.09	.64	-0.04	.84

SFC, stride foot contact; r, Pearson correlation coefficient.

Discussion

This study has shown several kinematic features associated with the pelvic rotation angle at SFC during the pitching motion. In pitchers with a larger pelvic rotation at SFC, the trunk bend to the contralateral side was increased. In addition, regarding the hip position on the throwing side, reduced flexion in all groups and increased adduction in the youth and high school groups were significantly correlated with an increase in pelvic rotation at SFC.

This study showed the association of the pelvic motion pattern with those of the trunk and hip. It has been shown that excessive contralateral trunk tilt is related to increased shoulder and elbow forces. In addition, adducted hip position on the throwing side can be a factor leading to the open foot position at SFC, which has been reported to induce the “opening up too soon” motion pattern.^{8,15} Our study results, along with the results of previous studies, address the significance of observation for kinematic patterns of the motion segments other than shoulder and elbow regions.^{14,18,19,21,22}

As for the mechanism to induce throwing injuries during the pitching sequence, Takagi et al²³ have indicated that excessive horizontal abduction of the shoulder at maximum external rotation increases anterior shear force in the joint. Wilk et al²⁸ showed that pitchers with insufficient shoulder external rotation had a 2.2-times greater risk for shoulder injuries. Premature pelvic rotation at SFC can be a reason or a compensation for problems at the shoulder and elbow. In addition, the kinematic pattern at the trunk and the hip shown in this study may also affect subsequent kinematics and kinetics in the upper extremities. To understand the pathomechanics related to throwing injuries in the kinematic chain,

the effect of motion pattern at the trunk and hip on subsequent shoulder and elbow motion and load should be examined.^{14,18,19}

The comparative analysis of the pitching kinematics in players of different ages/competition levels observed no significant difference for most of the kinematic parameters at SFC except trunk forward flexion and contralateral tilt across the different age and competition levels. The obtained results generally agree with those that have been reported in previous relevant studies.^{1,7,9,10,26}

As for the level-specific kinematic features, the amount of forward and contralateral tilts of the trunk at SFC were larger in the YP group than in the older and more skilled pitchers. This motion pattern may indicate immature motion strategy in this age/competition group. Aguinaldo et al¹ reported that pitchers in the younger age group rotated the trunk significantly earlier in the throwing phase compared with PPs. Urbin et al²⁵ showed that pitchers in this age group exhibited an inconsistent and variable trunk rotation pattern. Therefore, it is thought that intervention with an injury prevention training program focused on the trunk and pelvic motion can be important and effective, especially for pitchers in this age/competition group.

There are some limitations included in the design and contents of this study. First, although the study included a fairly large number of subjects ($n = 324$), the number of adult pitchers was relatively small compared with the number of younger pitchers. The lower incidence of statistical significance in the adult group may be due to the inadequate sample size. Moreover, due to the paucity of existing information, the power calculation for required sample size was not feasible.

Second, there are potential measurement errors and inconsistency included in the methodology of the motion analysis system, although these are inherent limitations when using this type of measurement system.

Third, the pelvic opening angle at SFC was the only parameter adopted for the timing of pelvic opening in this study. Inclusion of other parameters, such as angular velocity, may provide additional information. Moreover, future studies need to examine the effect of the increased pelvic opening at SFC on the subsequent motion and resultant shoulder/elbow loads as well as its significance in etiologies of throwing injuries.

Conclusions

Early pelvic rotation in the throwing motion sequence, as manifested by increased pelvic rotation at SFC, was correlated with changes in kinematic parameters at other motion segments such as increased trunk tilt and decreased hip flexion.

Disclaimer

The authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

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