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Timing of peak pelvis and thorax rotation velocity in baseball pitching

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Abstract The objective of the present study was to examine the magnitude and timing of peak pelvis and thorax rotations in achieving high throwing velocities in pitching fastballs. During the preseason (Test 1 or T1) and four months later (Test 2 or T2), kinematic analysis was performed on eight elite youth pitchers throwing fastballs. Peak rotation velocities of the pelvis and thorax were determined and separation time, defined as the time between the maximal rotation velocities of the pelvis and thorax, was calculated. Peak thorax rotation velocity was not associated with throwing velocity. However, separation time appeared to be significantly and positively associated with throwing velocity. Also, the changes in separation time from T1 to T2 were significantly and positively associated with the observed increase in throwing velocity from T1 to T2. There was no significant association between the changes in pelvis or thorax peak rotation velocities from T1 to T2 and the change in throwing velocity. Results indicate that the relative timing of pelvis and thorax peak rotation velocity in pitching fastballs in baseball is likely to be a determinant of throwing velocity in skilled pitchers.
Keywords : throwing, motion analysis, kinematics, performance

Introduction

In all overhand (or overhead)- throwing sports, and specifically in baseball pitching, the ability to deliver high-throwing speeds up to 100 mph is seen as an extremely valuable skill. The total body contributes to these high throwing velocities and has been described in different overhand throwing sports as the so-called 'kinematic chain'[1-4)]. It is, therefore, not surprising that throwing velocity is associated with several kinematic parameters not limited to those of the shoulder and arm. The position, translation and rotation of the pelvis are also important contributing factors during a throwing performance[5-9)]. The translation and subsequent rotation in the transverse plane of the pelvis together are used to initiate the rotation of the upper body[9-12)]. Multiple studies demonstrated the role of upper body rotation velocity in baseball pitching[7,8,11,13,14)], and the subsequent characteristics of shoulder and arm movements[15-20)]. While these studies aimed to investigate the roles of individual segment rotations separately in reaching high throwing velocities, they did not report on the timing of rotations *between* those segments, which is an important aspect of the working mechanism of the kinematic chain. More specifically, understanding the timing between pelvis and upper body rotation could lead to better understanding the kinematic chain in baseball pitching. Although this can be studied by assessing the onset of rotation of the pelvis and upper body, in relation to throwing velocity (in baseball) studies have been focusing on peak rotation velocities[7,8,11,13,14)], which are clearly an indication of the kinematic chain[2)].

The time interval between the peak rotation velocity of the pelvis and the peak rotation velocity of the thorax has been defined as separation or separation time (Fig. 1)[21,22)]. It has been suggested that with an increase in the separation time, there is more eccentric loading on the thorax, which could result in a higher throwing velocity[6,9,23,24)]. Based on video analysis, Sgroi et al.[22)] reported a positive association between separation of the hips and shoulders and throwing velocity. Urbin et al.[21)] reported in a between-subject study on variations in the timing of multiple segments in association with ball speed and upper extremity kinetic parameters. They demonstrated that increased time between peak angular velocities of the pelvis – defined as the line connecting the greater trochanters - and upper torso - defined as the line connecting the acromion processes

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- correlated with decreased ball speed. They also state that variations in the duration of this phase are related to decreased ball speeds [Urbin et al., p. 341]. In both studies, the movement of the shoulders was included in the approximated upper body rotation, thus upper body rotation was a combination of the movements of both the shoulder girdles and the thorax combined. To ascertain whether the findings on the timing of pelvis and upper body rotation in relation to ball speed in baseball pitching still hold with a more strict definition of the thorax segment, the present study focuses more closely on the timing of the peak rotation velocities of the pelvis and thorax, where the latter segment is defined based on recommendations of the International Society of Biomechanics (ISB), which implies the exclusion of shoulder motion (Appendices 1 and 2)[25].

The objective of the present study was to investigate whether the separation time between pelvis and thorax peak rotation velocity is associated with throwing velocity in fastball pitching. It was hypothesized that separation time is positively associated with throwing velocity. Measurements were performed on the same young (16 - 18 years) individuals in the preseason and midseason. It was expected that throwing velocity would increase in this time period because of seasonal training and growth effects. Therefore, additional - more convincing - evidence for an association between the separation time between pelvis and thorax peak rotation velocity and throwing velocity based on within-subject variation can thus be studied by exploring whether the *change* in the separation time between pelvis and thorax peak rotation velocity from preseason to midseason is associated with the *change* in throwing velocity.

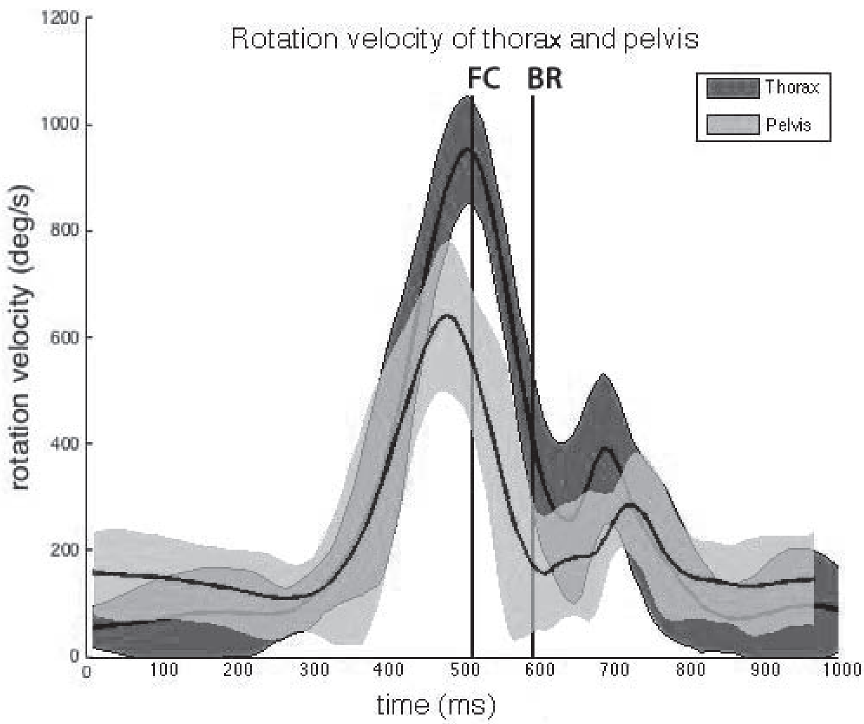


Fig. 1 Average rotation velocity profile (black line) of thorax and pelvis from all pitches measured at T1, surrounding areas are ± 2 SD. Vertical lines are stride foot contact (FC) and ball release (BR). Rotation velocity profiles of different pitches are synchronized at peak rotation velocity.

Appendix (1) Marker placement [See appendix (2) for figure].

Segment	Bony Landmark	
Pelvis (Right and Left)	Superior Iliac Anterior Spine	SIAS
	Superior Iliac Posterior Spine	SIPS
Thorax	Incisura Jugularis	IJ
	Processus Xiphoideus	PX
	Cervical Vertebrae 7	C7
	Thoracic Vertebrae 10	T10

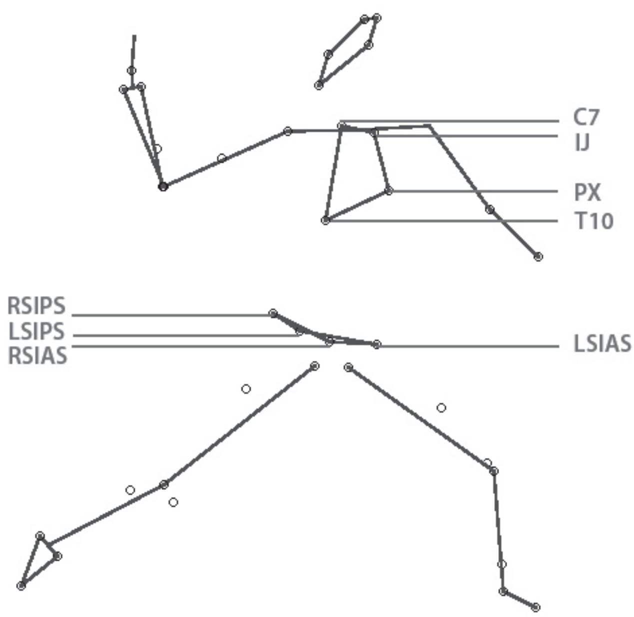
Material and Methods

Participants. Eight pitchers of the Dutch AAA team (age 16.1 ± 0.7 years, stature 181.7 ± 7.9 cm / 5'11" ± 3", bodyweight 76.9 ± 8.1 kg) participated in this study. These elite young pitchers are the best pitchers of their age group in The Netherlands. After having been informed of the aims and procedures of the experiments, all players and, for those below the age of 16, their legal representatives, signed an informed consent form. The Human Movement Sciences' local ethical committee approved this research project under reference ECB 2013-53.

Procedures. Measurements were performed in the Adidas MiCoach Performance Centre in Amsterdam. A 10-camera (T40S, 100Hz) VICON (Vicon Motion Systems Ltd., UK) motion capturing system was used to record 3D marker positions. The cameras were installed around a portable pitching mound to make the view as narrow as suitable, optimising the recording of all markers. Study aims and procedures were explained to the pitchers prior to being guided through a warm-up protocol. Pitchers performed a general warm-up of running and stretching, and a specific throwing warming-up, similar to a warm-up they would perform before a bullpen session. After the warm-up, retroflective markers needed for 3D kinematic analysis were attached. The pitchers only wore tight shorts and indoor shoes so markers could be attached directly to the skin with double-sided tape. The markers were attached following the plug-in-gait model, with additional markers on the throwing arm (see Appendices 1 and 2). Pitchers were asked to perform at least five throws on the mound to get used to the setup and the attached markers. Pitchers threw towards a catcher, who sat in catching position at the regular game distance (18.4 m). Subsequently, pitchers were asked to perform five fastball pitches. The study consisted of two recording sessions; the first session (T1) took place in February 2012 before spring training. The second session (T2) took place 19 weeks later in the first week of summer break. During this 19-week period players followed the regular training schedule of the national U-18 team, which consisted of 4 training sessions per week, and from mid April onward, also two matches per week.

Data analysis. Position data of the markers were exported from VICON and all calculations were performed in MATLAB (MathWorks, Natick, Massachusetts, USA). Pitches that were performed when markers came loose, or when a participant slipped from the mound, or did not hit the catchers' mitt, were excluded. If more than three pitches remained, the first and last pitch of the five was excluded to get three pitches for further processing. Before processing, landmark coordinates were splined with the standard MATLAB cubic spline interpolation function for missing data and filtered with a 4th order low-

Appendix (2) Placement of pelvis and thorax markers.



Appendix (3) Markers used for calculation of local coordinate systems.

Thorax	T10, C7, PX, IJ
x-axis	The line perpendicular to on y-axis and z-axis pointing forwards
y-axis	The line perpendicular to the plane formed by IJ, C7, and the midpoint between PX and T8, pointing to the left
z-axis	The line connecting the midpoint between PX and T10 and the midpoint between IJ and C7, pointing upward
Pelvis	RSPIS, LSIPS, RSIAS, LSIAS
x-axis	midpoint of SIPS → midpoint of SIAS
y-axis	RSIAS →LSIAS
z-axis	Perpendicular on x and y

pass recursive filter at 12.5 Hz to reduce the effects of sampling error. Segment local coordinate systems (LCS) were defined for the thorax and pelvis with the markers attached as recommended by ISB (Appendices 1 and 2)[25], axis were defined with x-axis in the throwing direction, y-axis from right to left and the z-axis pointing upward (Appendix 3). Segment angular velocities were directly calculated from the rotation matrices following Zatsiorski[26] (Eq. 1):

$$\tilde{\omega} = 0.5 * \left(\left(\dot{R} \times R' \right) - \left(R \times \dot{R}' \right) \right), \ \omega = \begin{bmatrix} \tilde{\omega}(3,2) \\ \tilde{\omega}(1,3) \\ \tilde{\omega}(2,1) \end{bmatrix}. \quad \text{(Eq. 1)}$$

R = rotation matrix expressing the orientation of the segment relative to a global coordinate system; $\dot{R}$ = the numerical derivative of rotation matrix R. []' = transposed rotation matrix. $\tilde{\omega}$ = 3 x 3 skew-symmetric matrix containing the three angular velocity components around the three main axes. ω = 3 x 1 rotation velocity vector [x,y,z]'.

The magnitude of the angular velocity was calculated as the norm of the angular velocity vector (Eq 2.):

$$\omega_{total} = [\ \omega(3,2)^{\wedge 2} + \omega(1,3)^{\wedge 2} + \omega(2,1)^{\wedge 2}]^{\wedge 0.5}. \quad \text{(Eq. 2)}$$

A 2nd order polynomial function ($y = a + bx + cx^2$) was fitted using 11 measured data points that consisted of 5 data points before and after peak angular velocity in order to obtain the functions' coefficients *a*, *b* and *c*. Based on these coefficients, the true moment in time of peak angular velocity (Eq. 3) and magnitude of peak angular velocity (Eq. 4) were analytically determined:

$$x = -b/2a \quad \text{(Eq. 3)}$$
$$y = a + bx + cx^2 \quad \text{(Eq. 4)}$$

Throwing velocity was calculated as the peak linear velocity of a marker attached to the tip of the middle finger of the throwing hand in the direction of the throw, therefore the calculated velocity is reported as 'fingertip velocity'.

Statistical analysis. First, the change of pelvis and thorax peak rotation velocity, separation time between pelvis and thorax maximal rotation velocity and fingertip velocity between the preseason (T1) and midseason (T2) were explored with simple linear regression analysis using GEE (Generalized Estimating Equations[27]) in SPSS (v 21.0.0.1, IBM Corporation, Armonk, NY, USA). The general simple linear regression equation was:

$$outcome = b_0 + b_1 * predictor \quad \text{(Eq. 5)}$$

GEE was used, as it is able to account for the dependency between the repeated throws within pitchers. An exchangeable working correlation matrix was used. In the GEE analysis, participants were incorporated as random factor to account for the dependency of the repeated trials within participants. Three fastball pitches per pitcher per recording session were used for the statistical analysis. Test 1 or Test 2 (T1 or T2) was entered into the regression model as categorical predictor variable (factor), while pelvis and thorax peak rotation velocity, separation between pelvis and thorax maximal rotation velocity and fingertip velocity were the continuous dependent variables. Regression coefficients (b_1) and corresponding 95% confidence intervals (CI) were determined and statistically tested using Wald chi-square statistics.

Whether pelvis and thorax peak rotation velocity and separation time between pelvis and thorax maximal rotation velocity were associated with fingertip velocity was also explored in a simple linear regression analysis using GEE. Pelvis and thorax peak rotation velocity and separation time were put in the regression model one by one as continuous predictor variables (covariates) while fingertip velocity was the continuous dependent variable. Thus, regression coefficients (b_1) and corresponding 95% CI were determined for each of the three predictor variables separately, i.e. pelvis and thorax peak rotation velocity and separation time. Data of both the preseason and midseason were pooled together in these analyses.

Comparable analyses were performed to investigate whether the change in pelvis and thorax peak rotation velocity and separation time between pelvis and thorax peak rotation velocity between the preseason (T1) and midseason (T2) measurements were associated with changes in fingertip velocity. Delta (change) scores were calculated by deducting the calculated values of every pitcher of T1 from the T2 values (Δ=T2−T1). The general simple linear regression equation was:

$$\Delta\ outcome = b_0 + b_1 * \Delta\ predictor \quad \text{(Eq. 6)}$$

Results

The average fingertip velocity, operationalized as the linear velocity of the tip of the middle finger, was 30.0 ± 1.3 m/s (67.1 ± 2.8 mph) at T1 (Table 1). At T2, fingertip velocity was significantly higher compared to T1 by 1.8, 95% CI: 0.9 - 2.7 m/s (4.1, 95% CI: 2.1 - 6.0 mph). The average thorax peak rotation velocity at T1 was 975 ± 53 °/s. A significant increase was also observed in thorax peak rotation velocity, which was 39 °/s (95% CI: 21 - 58 °/s) higher at T2 compared to T1. On average, pelvis peak rotation velocity changed 31 °/s (95% CI: -9 - 73 °/s) and separation time -5 ms (95% CI: -12.6 - 3.8 ms) from T1 to T2, but these findings were not significant p = .129 and p = .293, respectively.

Separation time was significantly associated with fingertip velocity (b1 = 0.105, 95% CI 0.072 - 0.138) (Table 2). Based on the resulting regression model, a 9.5 ms increase in separation time would result in 0.45 m/s (1 mph) increase in fingertip velocity. Pelvis peak rotation velocity was also significantly associated with fingertip

Table 1. Mean of throwing velocity, pelvis and thorax rotation velocity and separation for T1 and T2 and p-values.

	T1	T2	*p*-value
Throwing velocity (m/s)	30.0 ± 1.3	31.8 ± 1.4	<.001
Throwing velocity (mph)	67.1 ± 2.8	71.2 ± 3.2	<.001
Separation time (ms)	39 ± 9	34 ± 15	.293
Pelvis rotation velocity (°/s)	630 ± 68	661 ± 104	.129
z-component (axial rotation)	546 ± 77	616 ± 97	.004
x-component (lateral flexion)	170 ± 41	197 ± 82	.202
y-component (flexion/extention)	163 ± 64	181 ± 104	.307
Thorax rotation velocity (°/s)	975 ± 53	1014 ± 42	<.001
z-component (axial rotation)	825 ± 59	868 ± 89	.014
x-component (lateral flexion)	166 ± 73	179 ± 101	.878
y-component (flexion/extention)	450 ± 140	447 ± 189	.696

Note. T1, preseason; T2, midseason; p-value is of the regression coefficient (b1) for the difference between T1 and T2 as predictor of these outcome variables.

Table 2. Results of regression analyses (General Estimating Equations) concerning the associations of (changes in) pelvis and thorax peak rotation velocity and separation with (changes in) throwing velocity.

Throwing velocity $= b_0 + b_1$ x peak pelvis rotation velocity			
b_0	b_1	95 % CI b_1	p
59.128	0.015	0.001 – 0.030	.034
Throwing velocity $= b_0 + b_1$ x peak thorax rotation velocity			
b_0	b_1	95 % CI b_1	p
54.328	0.015	-0.022 – 0.51	.426
Throwing velocity $= b_0 + b_1$ x Separation			
b_0	b_1	95 % CI b_1	*p*
65.077	0.105	0.072-0.138	<.001
Δ Throwing velocity $= b_0 + b_1$ x Δ peak pelvis rotation velocity			
b_0	b_1	95 % CI b_1	p
3.784	0.013	-0.022 – 0.048	.454
Δ Throwing velocity $= b_0 + b_1$ x Δ peak thorax rotation velocity			
b_0	b_1	95 % CI b_1	p
4.532	-0.003	-0.50 – 0.043	.885
Δ Throwing velocity $= b_0 + b_1$ x Δ Separation			
b_0	b_1	95 % CI b_1	*p*
5.702	0.238	0.197 – 0.279	<.001

Note. b_1, regression coefficient; CI, the 95% confidence interval of b_1.

velocity (b1 = 0.015, 95% CI 0.001 - 0.030). Based on the resulting regression model, a 67 °/s increase in peak pelvis rotation velocity would result in 0.45 m/s (1 mph) increase in fingertip velocity. Within this group of young pitchers, thorax peak rotation velocity was not associated with fingertip velocity (Table 2, Fig. 2).

The change in separation time from T1 to T2 was significantly and positively associated with the change in fingertip velocity with $b_1 = 0.238$ (95% CI: 0.197 - 0.279) (Table 2). The regression coefficient indicates that a 4.2 ms increase in change in separation time would result in 0.45 m/s (1 mph) increase in change in fingertip velocity. The changes in pelvis and thorax peak rotation velocity from T1 to T2 were not associated with changes in fingertip velocity.

Discussion

In the studied sample of Dutch AAA pitchers, separation time between thorax and pelvis peak rotation velocity was positively associated with fingertip velocity in fastball pitching. We also observed a significant and positive association between the within subject change in separation time and the within subject change in fingertip

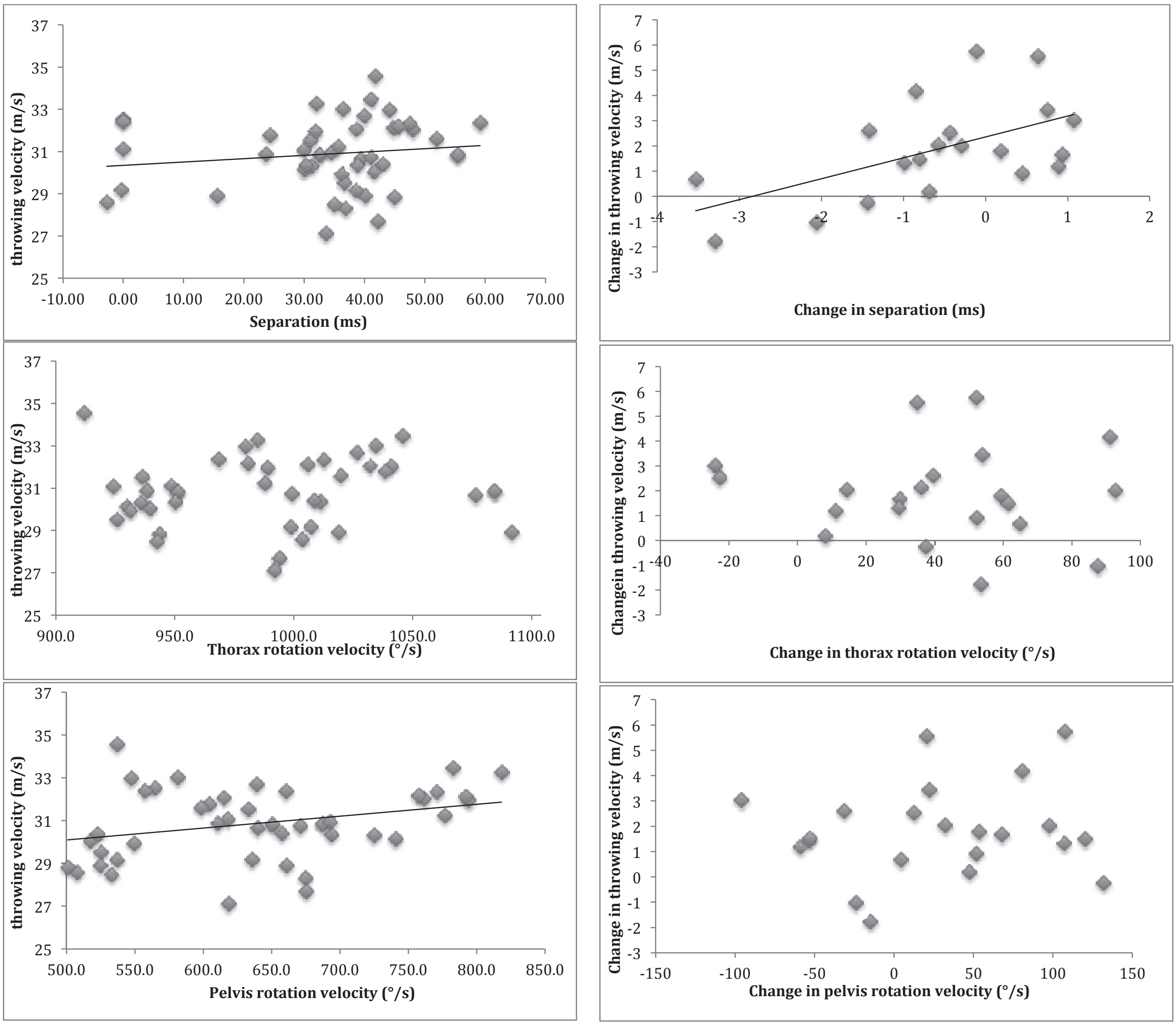


Fig. 2 Left column: Thorax rotation velocity (A), pelvis rotation velocity (B) and separation (C) plotted against throwing velocity. Right column: Changes in thorax (D) and pelvis rotation velocity (E) and separation (F) plotted against changes in throwing velocity between T1 and T2. All graphs include trend lines based on the results of the regression analyses.

velocity between the two measurements. This suggests that when peak rotation velocity of the thorax is observed later in time, compared to peak rotation velocity of the pelvis, separation time increases fingertip velocity, resulting in an increase in throwing velocity. It should be kept in mind that there is likely to be an optimum for separation time and the predictions of the regression analyses should, thus, not be extrapolated outside the actual range of separation times that was observed in the present study (-10 to 60 ms).

This study underlines the reported positive association between throwing velocity and separation of the pelvis and upper body as shown by Sgroi et al.[22]. While using video analyses, they demonstrated that pitchers who generally rotated the shoulders more than the pelvis showed the highest ball velocities. However, in contrast to the results of Sgroi et al.[22] and the present study, Urbin et al.[21] discussed that an increased separation time is associated with a decreased throwing velocity, thus a negative association. The reported mean separation time of Urbin et al. (39 SD 19 ms) was comparable to the value in this study (39 SD 9 ms). Firstly, whereas the Urbin et al.[21] study used between-subject variation, in the present study the association between separation time and throwing velocity was studied using both between and within subject variation. A positive association was observed between separation time and throwing velocity. This significant result was found using GEE that includes both between- and within-subject variation – because of repeated measures due to several trails on two occasions – in one analysis[28]. However, a positive association was also observed when we put more emphasis on the within-subject variation, this was done when we studied the changes from preseason to midseason. Secondly, in the present study, thorax rotation velocity was determined using markers attached to landmarks of the spine and the sternum, as recommended by ISB[25]. Previous studies used markers on the left and right acromion; upper body rotation then would be a mixture of thorax rotation, scapular rotation and shoulder girdle protraction and retraction. As a result, the upper body, i.e. upper torso, peak rotation velocity estimated using acromion markers will be somewhat higher and the actual thorax peak rotation velocity will have a lower peak rotation velocity. Indeed, the observed thorax peak rotation velocity in the present study of 982 ± 51°/s was slower than the peak rotation velocity of the upper body estimated using acromion markers reported in literature (1183 ± 109 °/s[6], 1227 ± 72 °/s[14], 1190 ± 100 °/s[29]). This difference might affect the estimated time of occurrence of thorax peak rotation velocity, and therefore, also affect the actual separation time. Considering the explorative nature of the present study, the relatively small sample size and the complexity of measuring the shoulder girdle, the issue of upper body or thorax rotation velocity in relation to marker placement warrants further study.

In the present sample of youth pitchers the association between pelvis rotation velocity and throwing velocity was significant and positive. The association between thorax peak rotation velocity and throwing velocity, and the associations between the changes in pelvis and thorax peak rotation velocities from T1 to T2, and the change in throwing velocity from T1 to T2, were not significant. In line with these findings, Matsuo et al.[14] found no association between maximum pelvis and thorax angular velocity and throwing velocity in a group of 127 college and professional baseball pitchers. However, it is reasonable to assume that the high rotation velocity of pelvis and thorax is a prerequisite for high throwing velocity, and differences in throwing velocity within a homogeneous group are likely based on technique differences. The effect of age and skill level on pelvis and thorax rotation velocity has been studied by Stodden et al.[6]. They found an increase in pelvis and thorax rotation velocity between groups of varying age between 3 and 15 years. Furthermore, Fleisig et al.[29] compared pelvis and thorax rotation velocity between four age groups that all significantly differed in throwing velocity. Only the high-school age group (15-20 years) showed a significantly lower upper-torso rotation velocity and only the professional group (20-29 years) showed a higher pelvis rotation velocity than the other three groups. In these studies, with a cross-sectional design, it was demonstrated that age and skill level are positively associated with rotation velocity of the segments and throwing velocity. In the present study, the pitchers were part of a relatively small and homogeneous group and are the most talented pitchers of their age group (15-18 years. The average finger tip velocity of the elite youth pitchers in this study of 71.2 mph (31.8 m/s) is likely a underestimation of their actual ball velocity when pitching fastballs.) They already showed high thorax rotation velocities and, not surprisingly, the inter-individual differences in rotation velocity between pitchers were relatively small. This might explain that no association between the maximal rotation velocities and throwing velocity was observed, whereas for separation time - as a measure of throwing technique - the association was positive and significant. Moreover, this association was also found within pitchers as we studied the changes from preseason to mid-season. The association between the change in separation time and the change in throwing velocity, even within this small and homogeneous group, indicates that there could be a causal relationship between the two. This could be useful in, for instance, developing new training protocols for elite athletes to achieve higher throwing velocities.

"Further studies, with respect to the role of the kinematic chain in pitching, should include other segments and their inter-segmental timing in the kinematic chain. To quantify the inter-segmental timing, especially of the upper extremities, it is recommended to use higher sample frequencies. In this study potential sampling issues were resolved using an analytical approach. Besides quantifying the inter-segmental timing of the kinematic chain, additional calculation of the power flow from segment to segment could give insight into the energy transfer between the segments. This energy transfer, for a tennis serve, was studied by Martin et al.[30] using a power-flow model. In baseball pitching, this model could give more insight in how the energy transfer is affected by separation time, and this insight may result in higher throwing velocity. The importance of the separation time between pelvis and thorax, as observed in the present study, as well as between other segments in the kinematic chain, could initiate the development of new training protocols that aim for achieving higher throwing velocities. Specific exercises and instructions could be developed to help train the sequential rotation of, for instance, the hips and thorax to achieve more, and ultimately optimal, separation time. As learning proper mechanics is also considered helpful in the prevention of injuries[31], a focus on the sequential rotations of segments according to the kinematic chain in learning fast pitching in baseball might also result in safer throwing.

Conclusion

The relative timing of pelvis and thorax peak rotation velocity in pitching fastballs in baseball is likely to be associated with throwing velocity in elite youth baseball pitchers. Separation of segmental peak rotations deserves to be focused on in scientific research as well as in developing training protocols in baseball pitching.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this article.

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