The effects of relative trunk rotation velocity on ball speed and elbow and shoulder joint torques during baseball pitching

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ABSTRACT

In baseball pitching, suppressing trunk rotation while rotating the pelvis in the early phase of arm cocking is important for throwing a fast ball. However, quantitative evaluation of trunk rotation during pitching has not been established, and its associations with elbow and shoulder torques are unclear. The purpose of this study was to examine the correlation of a new measure of trunk rotation suppression with ball speed and elbow and shoulder torques during pitching. Eighteen adult male baseball pitchers (21.7 ± 1.2 years old) participated. Three qualified pitches were analysed using a three-dimensional motion capture system. Trunk rotation velocity, normalised to the peak velocity, was derived at the time of peak pelvic velocity. Pearson's correlation coefficient was used to determine correlations. The normalised trunk rotation velocity at the peak pelvic velocity was significantly correlated with elbow valgus torque (R = -0.508, P = 0.032), shoulder external rotation torque (R = -0.507, P = 0.032) and ball speed (R = -0.504, P = 0.033). A smaller normalised trunk rotation angular velocity at the time of peak pelvic rotation velocity could increase ball speed but may also increase elbow and shoulder torques among pitchers who demonstrate trunk rotation after foot contact.

Keywords: baseball pitching; trunk rotation movement; ball speed; shoulder external rotation; elbow valgus

INTRODUCTION

Elbow and shoulder injuries are common among baseball players at all ages and skill levels (Dick et al., 2007; Posner et al., 2011; Takagishi et al., 2017; Takagishi et al., 2019; Wasserman et al., 2019), although pitchers have higher incidence rates of elbow and shoulder injuries and undergo more surgeries than fielders (Chalmers et al., 2019; Fares et al., 2020). Elbow and shoulder injuries among pitchers have been reported to include ligament injuries and muscle strains (Fares et al., 2020; Saper et al., 2018). These injuries are mostly caused by overuse mechanisms involving external loads, such as elbow valgus and shoulder external rotation torques (Agresta et al., 2019; Anz et al., 2010; Sabick et al., 2004). Repetitive elbow valgus torque during pitching strains the ulnar collateral ligament, which is the primary ligamentous stabiliser of the medial elbow (Ahmad et al., 2013; Hattori et al., 2021), and excessive shoulder external rotation torque could cause shoulder injury (Fleisig et al., 1996).

Large elbow and shoulder torques are associated with trunk rotation as well as faster ball speeds (Aguinaldo et al., 2007; Davis et al., 2009; Fleisig et al., 1999; Fleisig et al., 2006; Hurd et al., 2012). Pitchers who initiated trunk rotation relative to the pelvis before foot contact showed significantly larger elbow valgus torques and shoulder internal rotation torques than pitchers who initiated trunk rotation after foot contact (Aguinaldo et al., 2007; Aguinaldo et al., 2009; Davis et al., 2009). In fact, early trunk rotation before foot contact was associated with an increased risk of elbow and shoulder injuries (Douoguih et al., 2015). Therefore, evaluation and modification of the onset of trunk rotation motion are important for the prevention of elbow and shoulder injuries in pitching. However, the sequence of the peak pelvic and trunk rotation velocities is also important for pitching (Putnam, 1991; Stodden et al., 2006). In the pitching motion, the appropriate sequence of the peak pelvic and trunk rotation velocities enhances the efficiency of transferring the momentum produced by the lower limbs to the ball through the pelvis, trunk, and upper limbs and increases ball speeds (Putnam, 1991; Stodden et al., 2006). Therefore, the pelvic and trunk rotation velocities during the arm-cocking phase may also be associated with elbow and shoulder torques.

The evaluation of pelvic and trunk rotation during the arm-cocking phase has been investigated mainly in terms of their association with ball speeds in pitching (Graaff et al., 2018; Sgroi et al., 2015; Urbin et al., 2013). Having the trunk remain facing the third base while the pelvis rotates and faces the home plate for a right-handed pitcher was significantly associated with a faster ball speed (Sgroi et al., 2015). The time length between the peak pelvic and trunk rotation velocities was devised to evaluate the sequence of the pelvic and trunk rotation velocities (Graaff et al., 2018; Urbin et al., 2013). However, the relationships of this time length and ball speeds are inconsistent (Graaff et al., 2018; Urbin et al., 2013). A longer time between the peak pelvic and trunk angular velocity was significantly associated with faster throwing hand speed (Graaff et al., 2018), whereas another study reported that this time length was not associated with a faster ball speed (Urbin et al., 2013). Therefore, it has not been established how to quantitatively evaluate pelvic and trunk rotation velocities during the arm-cocking phase. Furthermore, the associations of pelvic and trunk rotation velocities with elbow and shoulder torques are unclear.

As a new evaluation of pelvic and trunk rotation velocities during the arm-cocking phase, we normalised the trunk rotation angular velocity by its peak value. A smaller normalised trunk rotation velocity at the peak pelvic rotation angular velocity represents the degree to which the trunk rotation velocity is suppressed when the pelvis is rotating at the peak velocity, whereas a larger normalised trunk rotation velocity at the peak pelvic rotation angular velocity indicates that the trunk and pelvis rotate simultaneously. Therefore, the normalised trunk rotation velocity at peak pelvic rotation angular velocity could represent the pelvic and trunk rotation movement sequence during the arm-cocking phase (Putnam, 1993; Stodden et al., 2006).

The purpose of this study was to examine the relationship of the normalised trunk rotation velocity with ball speed and elbow and shoulder torques during pitching. It was hypothesised that the normalised trunk rotation velocity at the peak pelvic rotation velocity would be positively correlated with elbow valgus torque and shoulder external rotation torque and negatively correlated with ball speed.

MATERIALS AND METHODS

Participants

To determine the sample size, an intermediate power analysis was performed using 80% power, an α level of 0.05, and an effect size of 0.6 (G*Power 3.1., Institute of Experimental Psychology, Heinrich Heine University, Dusseldorf, Germany). The assumed effect size was based on the results of our pilot study. According to the results of the power analysis, a sample size of 17 was needed. A total of 18 male pitchers playing in a competitive baseball team participated in this study (13 collegiate and 5 regional baseball team pitchers; age, 21.7 ± 1.2 years; height, 174.7 ± 6.1 cm; body mass, 73.2 ± 7.7 kg) (Table 1). The inclusion criteria were pitchers who were overhand throwers, had played for at least 2 baseball seasons and were aged between 18 and 25 years (not including high-school players). The mean pitching experience was 7.9 ± 3.5 years. All participants had been pitchers for at least 2 baseball seasons, and the mean pitching experience was 7.9 ± 3.5 years. The exclusion criteria were any elbow or shoulder injury in the last 6 months or a history of upper-limb or trunk surgery. Based on a previous study (Olsen et al., 2006), elbow or shoulder injury was defined as (1) shoulder or elbow pain lasting more than 2 weeks, (2) shoulder or elbow pain that caused them not to play in a game or practice, or (3) recurrent shoulder or elbow pain. The participants were recruited on a voluntary basis through posters posted at the university gymnasiums or announcements from the regional amateur baseball association. Written informed consent was obtained from all participants before participation. The present study was approved by the Institutional Review Board at Institutional Review Board of Faculty of Health Sciences, Hokkaido University (approval number: 19-110).

Instrumentation

A three-dimensional motion capture system (Vicon MX, Vicon Motion Systems, Oxford, UK) was used to capture the movement. Fourteen infrared cameras (Vantage camera, Vicon Motion Systems) were used to track reflective markers attached to the participant at a rate of 200 Hz. Two force plates (OR6, AMTI, Watertown, MA, USA) planted and fixed on the floor were used to record ground reaction forces from the stride foot at 1,000 Hz, and the force data were synchronised with the kinematic data. A radar gun (SGR110, SSK Corp., Osaka, Japan) was used to record ball speed.

Procedures

Data collection took place inside a research laboratory. The participants were given enough time to warm up as they normally would before practice or games (e.g., jogging, stretching, warm-up throws). Then, 35 reflective markers were placed on the spinous process of the seventh cervical vertebra (C7), spinous process of the tenth thoracic vertebra (Th10), sternal notch, xiphoid process, head, bilateral acromia, lateral epicondyles of the humerus, radial processes, ulnar processes, second metacarpal on the hands, anterior superior iliac spines (ASIS), posterior superior iliac spines (PSIS), lateral femoral epicondyles, thighs, lateral malleoli, shanks, second metatarsal heads, and heels. The markers on the nonthrowing hand and both feet were placed over the estimated locations on a glove or on shoes, respectively. All participants used the glove or shoes that they usually wore.

Once all markers were placed, the participants practised pitching until they were ready to pitch at maximum effort. Pitching was performed on the flat floor towards a circular pitching target with a diameter of 0.3 m placed 10 m from the pitching line at a height of 0.8 m from the floor. For the pitching trials, the participants pitched fastballs from the set position. The participants were instructed to pitch as fast and as accurately as possible while aiming at the target. The participants continued to pitch until a minimum of 3 qualified pitches were captured. As a result, participants pitched from 3 to 6 fastballs. The participants were allowed to rest between pitches if needed.

Data Processing and Reduction

Kinematics and kinetics were analysed using Vicon Nexus automatic digitization software (version 2.1; Vicon Motion Systems). Raw three-dimensional marker coordinate data were filtered through a Woltring filter using a cut-off frequency of 10 Hz (Anz et al., 2010). Kinematics were calculated using the Cardan sequence (flexion/extension, adduction/abduction, and internal/external rotation). Angles of the pelvis and trunk were calculated relative to the laboratory coordinate system. The segment coordinate systems were defined based on the Vicon Plug-in Gait marker configuration. The origin of the pelvic coordinate system was located at the midpoint of the bilateral ASIS markers (Davis et al., 1991). The Y-axis of the pelvic coordinate system was oriented from the right ASIS marker to the left ASIS marker. The X-axis of the pelvic coordinate system was oriented forwards from the midpoint of the bilateral PSIS markers to the origin of the coordinate system. The Z-axis was oriented upwards, perpendicular to the Y- and X-axes. The origin of the thoracic coordinate system was located at the sternal notch with an offset of half a marker diameter (7 mm) backwards along the X-axis, defined as the direction from the midpoint of C7 and T10 to the midpoint of the sternal notch and xiphoid process. The Z-axis for the thorax was oriented upwards, defined as the direction from the midpoint of the xiphoid process and T10 to the midpoint of the sternal notch and C7. The Y-axis was oriented leftwards, perpendicular to the X- and Z-axes. To define the coordinate systems of the humerus and forearm, three virtual markers of the shoulder, elbow, and wrist joint centres were calculated. The virtual marker of the shoulder joint centre was calculated by shifting the acromion marker downwards by the shoulder offset value. The downwards direction was perpendicular to the line from the thoracic origin to the acromial marker and the X-axis of the thoracic coordinate system. The offset value was the distance between the acromion and the humeral head centre measured by the same physical therapist (T.I.) for each participant, plus half the marker diameter (7 mm). The virtual marker of the elbow joint centre was calculated by shifting the lateral epicondylar marker medially by the elbow offset value. The direction of shifting was determined such that a line from the elbow joint centre to the shoulder joint centre and a line from the elbow joint centre to the lateral epicondylar marker were perpendicular on the plane that was defined by the shoulder joint centre, elbow marker and the construction vector. The construction vector was perpendicular to the plane defined by the shoulder joint centre, the elbow marker, and the midpoint of the two wrist markers and passed through the elbow marker. The elbow offset value was half the distance between the lateral and medial epicondyles of the humerus measured by the same physical therapist (T.I.) for each participant, plus half the marker diameter (7 mm). The virtual marker of the wrist joint centre was offset towards the palmar side from the midpoint of the two wrist markers along a line perpendicular to both the line connecting the two wrist markers and a line from the midpoint of the two wrist markers to the elbow joint centre. The wrist offset value was half the thickness of the wrist measured by the same physical therapist (T.I.), plus half the marker diameter (7 mm). The origin of the humeral coordinate system was located at the elbow joint centre, and the Z-axis was defined as the direction from the elbow joint centre to the shoulder joint centre. The Y-axis for the humerus was a cross product between the Z-axis and the line between the elbow joint centre and the wrist joint centre. The X-axis was the direction perpendicular to the Y- and Z-axes. The origin of the forearm coordinate system was located at the wrist joint centre. The Z-axis was the direction from the wrist joint centre to the elbow joint centre. The Y-axis was defined as the Y-axis of the humerus segment. The X-axis was perpendicular to the Y- and Z-axes.

The external joint torques of the elbow and shoulder were calculated by inverse dynamics analysis (Winter, 1980). The arm-cocking phase was defined as the time from foot contact to maximum shoulder external rotation (Fleisig et al., 1996; Fleisig et al., 2006). Foot contact was identified as the instant when the vertical ground reaction force from the front foot exceeded 10 N (Oyama et al., 2014).

Following data reduction, the peak angular velocities of the axial rotation of the pelvis and trunk were calculated using MATLAB (MathWorks, Natick, MA, USA) as follows (Winter, 2009):

$$\omega_i = \frac{\theta_{i+1} - \theta_{i-1}}{2\Delta t} \ [deg/sec]$$

where ω represents the angular velocity of the axial rotation of the pelvis and trunk, θ represents the angle of axial rotation of the pelvis and trunk, i is the frame number, and Δt is the time between adjacent frames (0.005 sec). In addition, the normalised angular velocity of the pelvis and trunk were calculated relative to their peak angular velocities. The normalised trunk rotation velocity at the time of peak pelvic rotation velocity was derived (Fig. 1).

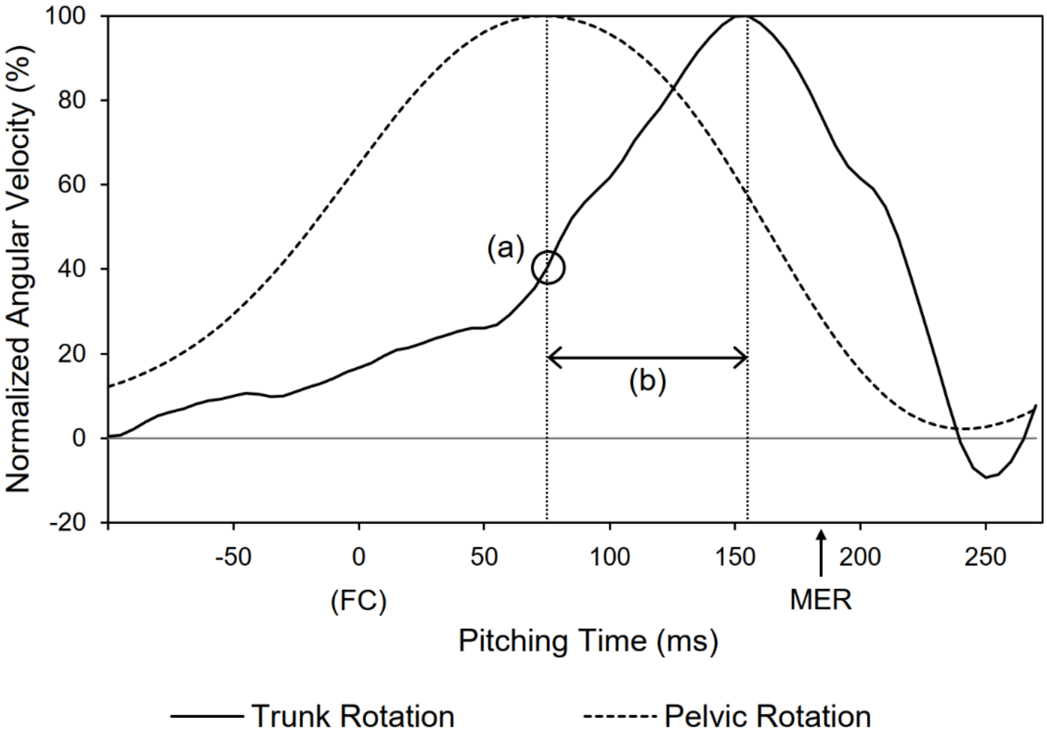

Figure 1. Normalised trunk rotation velocity and the length of time during pitching. (a) Normalised trunk rotation velocity at peak pelvic rotation velocity and (b) the length of time from the peak pelvic rotation velocity to the peak trunk rotation velocity.
FC: foot contact; MER: maximum shoulder external rotation

The normalised trunk rotation velocity at the time of peak pelvic rotation velocity represents the degree to which trunk rotation is suppressed when the pelvic rotation velocity reaches its peak. Additionally, the length of time from the peak pelvic rotation velocity to the peak trunk rotation velocity and the onset time of trunk rotation were also calculated to compare the findings of this study with those of previous studies (Aguinaldo et al., 2007; Aguinaldo et al., 2009; Graaff et al., 2018; Urbin et al., 2013). In addition, the onset time of trunk rotation was calculated as the time from foot contact to the peak trunk rotation angle relative to the pelvis in the pitching direction (Aguinaldo et al., 2007; Aguinaldo et al., 2009). The peak external elbow valgus and shoulder external rotation torques were analysed during the arm-cocking phase (Fleisig et al., 1995). The external elbow valgus and shoulder external rotation torques were normalised by each participant's body height and mass (Derrick et al., 2020). The average of the 3 pitches was used for data analysis (Post et al., 2015).

Statistical Analysis

IBM SPSS (version 22, IBM, Armonk, NY, USA) was used for the statistical analysis. The Shapiro–Wilk test of normality was conducted to investigate the normality of the data. Since normality was observed for all variables, Pearson's correlation analysis was used to determine the correlations of the normalised trunk rotation velocity, the length of time from the peak pelvic rotation velocity to the peak trunk rotation velocity and the onset time of trunk rotation with ball velocity and the peak elbow valgus and shoulder external rotation torques. Correlation coefficient thresholds of 0.1, 0.3, 0.5, 0.7, and 0.9 were interpreted as small, moderate, large, very large, and extremely large, respectively (Hopkins et al., 2009). The significance level was set to less than 5%.

RESULTS

The normalised trunk rotation velocity at the time of peak pelvic rotation velocity had a significant negative correlation with ball speed (*R* = -0.504, *P* = 0.033, Fig. 2a), elbow valgus torque (*R* = -0.508, *P* = 0.032, Fig. 2b), and shoulder external rotation torque (*R* = -0.507, *P* = 0.032, Fig. 2c). These correlations indicate that a smaller normalised trunk rotation velocity was associated with a faster ball speed and larger elbow valgus and shoulder external rotation torques. A longer time from the peak pelvic rotation velocity to the peak trunk rotation velocity was correlated with a faster ball speed (*R* = 0.473 *P* = 0.047, Fig. 3a) but was not correlated with a higher elbow valgus or shoulder external rotation torque (Fig. 3b and c). The onset time of trunk rotation had no significant correlation with ball speed or elbow valgus or shoulder external rotation torque (Fig. 4).

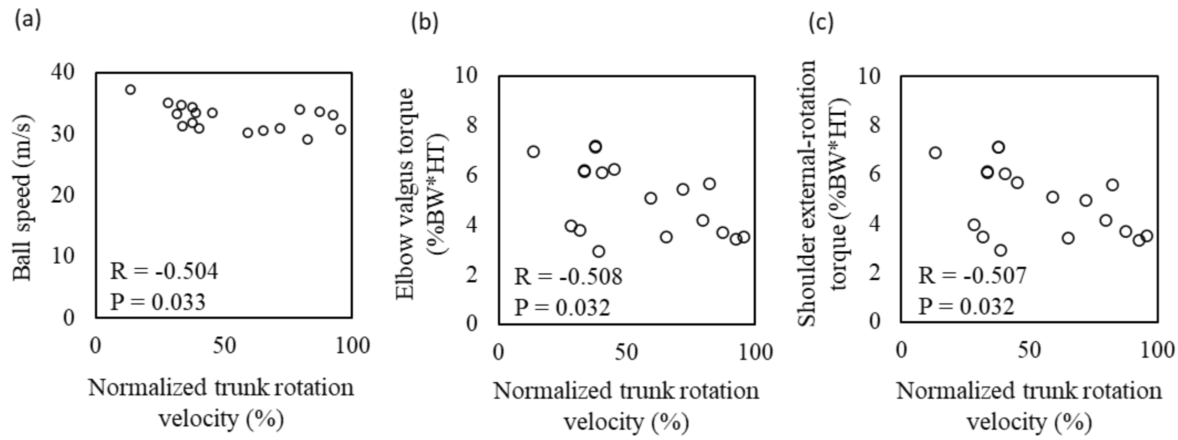

Fig. 2 Correlation between the normalised trunk rotation velocity and (a) ball speed, (b) elbow valgus torque, and (c) shoulder external rotation torque. The normalised trunk rotation velocity

had significant negative correlations with ball speed and elbow valgus and shoulder external rotation torques.

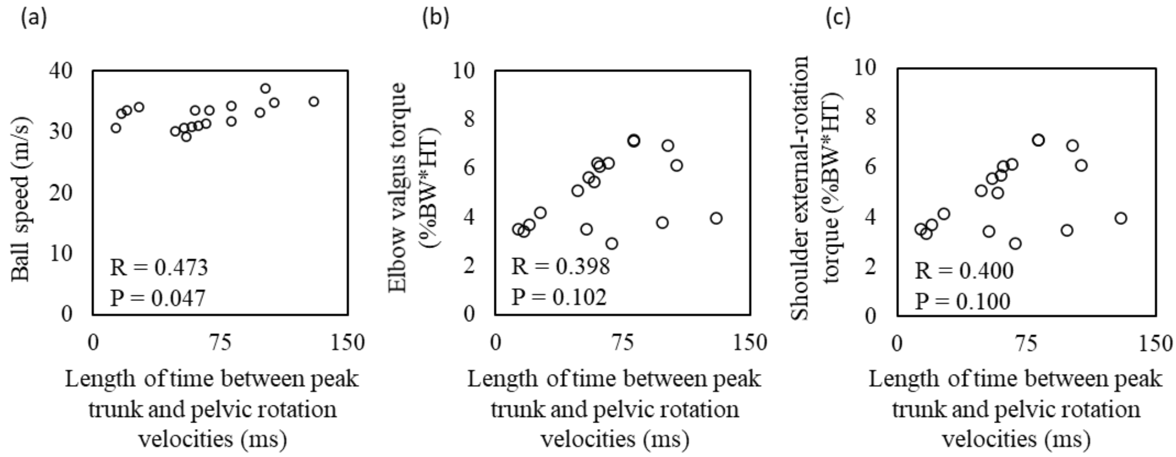

Fig. 3 Correlation between the length of time between the peak trunk and pelvic rotation velocities and (a) ball speed, (b) elbow valgus torque, and (c) shoulder external rotation torque. The length of time between the peak trunk and pelvic rotation velocities had a significant positive correlation with the ball speed.

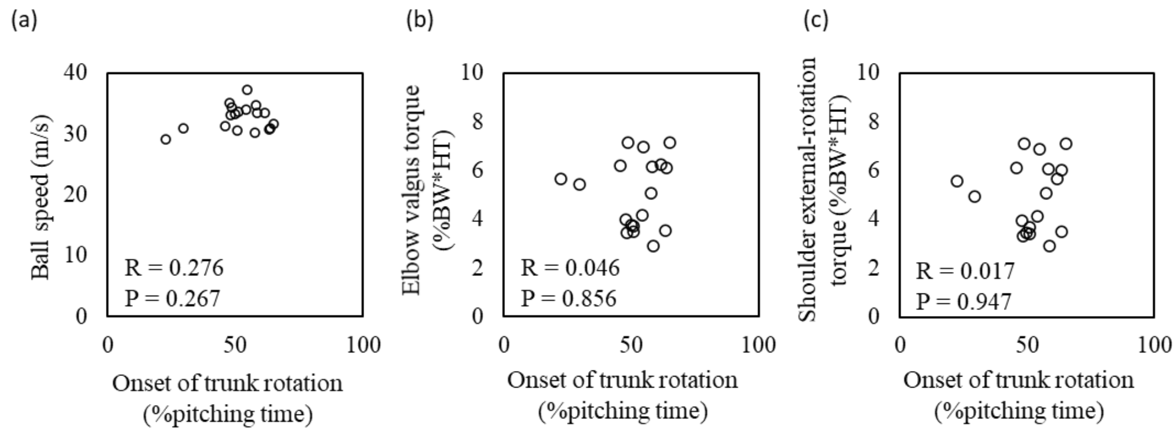

Fig. 4 Correlation between the onset of trunk rotation and (a) ball speed, (b) elbow valgus torque, and (c) shoulder external rotation torque. The onset of trunk rotation had no significant

correlation with ball speed or elbow and shoulder external rotation torques.

DISCUSSION AND IMPLICATIONS

The results of the present study showed that a smaller normalised trunk rotation velocity at peak pelvic rotation velocity was significantly associated with a faster ball speed, which supported our hypothesis. However, in contrast to the hypothesis, a smaller normalised trunk rotation velocity at the peak pelvic rotation velocity is associated with larger peak elbow valgus and shoulder external rotation torques.

The present result indicates that suppressed trunk rotation during pelvic rotation movement was associated with a faster ball speed. Although the peak trunk rotation angular velocity was an important factor in achieving a faster ball speed (Bullock et al., 2020), the suppression of trunk rotation during the arm cocking phase was also considered an important factor in faster ball speed (Graaff et al., 2018; Sgroi et al., 2015). Suppressing trunk rotation during pelvic rotation contributes to better transfer of momentum produced by the lower limbs to the ball through the pelvis, trunk, and upper limbs in pitching (Sgroi et al., 2015).

The present study used the normalised trunk rotation angular velocity to evaluate the suppression of trunk rotation because the peak magnitude of the trunk rotation angular velocity may affect the absolute value of the trunk rotation angular velocity at the peak pelvic rotation velocity. A pitcher with a larger peak trunk rotation angular velocity may have a large absolute trunk rotation angular velocity even if the trunk rotation angular velocity was suppressed relative to its peak magnitude. Therefore, the angular velocity of trunk rotation at the peak pelvic rotation angular velocity was normalised by its peak magnitude. Moreover, the correlation between the normalised trunk rotation angular velocity and ball speed found in our study was large (Hopkins et al., 2009). Thus, the normalised trunk rotation velocity at peak pelvic rotation velocity would be useful for objectively evaluating the suppression of the trunk rotation velocity during the arm-cocking phase.

A smaller normalised trunk rotation velocity was significantly associated with larger elbow valgus and shoulder external rotation torques. In a previous study, pitchers who rotated their trunk before foot contact applied larger elbow valgus and shoulder internal rotation torques than those who rotated their trunk after foot contact (Aguinaldo et al., 2007; Aguinaldo et al., 2009). Based on these findings (Aguinaldo et al., 2007; Aguinaldo et al., 2009), it was hypothesised that a high normalised angular velocity at the time of peak pelvic rotation velocity, which is presumably linked to early trunk rotation, would be associated with high elbow valgus and shoulder external rotation torques. However, the results were contrary to the hypothesis and suggested that suppressing trunk rotation during pelvic rotation could be associated with larger elbow valgus and shoulder external rotation torques. One possible explanation for this discrepancy between the present and previous studies is that no participants in the present study showed early trunk rotation before foot contact (i.e., negative onset of trunk rotation). Suppressed trunk rotation during the arm cocking phase may not decrease elbow and shoulder torques among pitchers who demonstrate trunk rotation after foot contact. Otherwise, a faster ball speed may lead to lower elbow and shoulder torques simply due to the smaller ball speed.

The length of time between the peak angular velocities of pelvic and trunk rotation was also reported as the assessment of suppressed trunk rotation during the arm cocking phase. The results of the present study showed a significant correlation between the length of time and ball speed, which is consistent with a previous study (Graaff et al., 2018) but inconsistent with another study (Urbin et al., 2012). The length of time would be affected by the total pitching time. The time from the peak pelvic rotation velocity to the peak trunk rotation velocity may be longer in slower pitching motion than in faster pitching motion. Therefore, the length of time of the angular velocities of pelvic and trunk rotation may not fully represent the suppression of trunk rotation during pelvic rotation. Thus, the normalised trunk rotation angular velocity may be a good alternative to quantifying the timing of trunk motion during pitching that accounts for the overall speed/length of the pitching motion.

Regarding clinical implications, the results of this study indicated that a smaller normalised trunk rotation velocity was associated not only with a faster ball speed but also with larger elbow valgus and shoulder external rotation torques. Larger external elbow valgus and shoulder external rotation torques are considered risk factors for elbow and shoulder injuries (Agresta et al., 2019; Anz et al., 2010; Sabick et al., 2004). Therefore, although an emphasis on suppressed trunk rotation in the cocking phase may benefit in increasing ball speed, the risk of elbow and shoulder injury should be acknowledged. Pitchers performing pitching while suppressing trunk rotation require the strength of elbow varus and shoulder internal rotation muscles to resist elbow valgus and shoulder external rotation torques during pitching and stabilise each joint (Fleisig et al., 1995; Fleisig et al., 1996; Park et al., 2004; Udall et al., 2009).

This study has some limitations. First, this study was cross-sectional. Therefore, the cause-effect relationship of trunk rotation movement with ball speed and elbow valgus and shoulder external rotation torques is unclear. In future studies, the effect of pelvic and trunk rotation interventions on ball speed and elbow and shoulder loading and the relationship of pelvic and trunk rotational velocities with the incidence rates of elbow or shoulder injuries need to be investigated. Second, the present study examined pitching on a flat floor towards a circular target. In an actual game, the pitcher wears spikes and throws from a mound into a strike zone, a distance of 18.44 m. A previous study demonstrated that the timing of pitching events in the pitching cycle and peak shoulder and elbow joint angular velocity and torques were different between pitching from a mound and from flat ground (Nissen et al., 2013). In addition, the reliability and measurement error of the normalised trunk rotation velocity have not been established. Further studies are needed to investigate the reliability in a closer situation to the actual outdoor pitching. Fourth, the sample size was generally considered small for a correlational analysis, although this was determined by our pilot study. Fifth, overhand throwing was determined by participants' self-reports and examiner's visual assessments, and the arm slot was not calculated in the present study. Finally, we investigated the correlation relationships without adjustment for *P* values, as in other similar studies examining the association between trunk kinematics and pitching speed, elbow valgus torque and shoulder external rotation torque (Aguinaldo et al., 2009; Leura et al., 2020). However, the repeated tests increase the probability of a study-wise type I error.

CONCLUSIONS

The smaller normalised trunk rotation velocity at peak pelvic rotation velocity was associated with larger elbow valgus and shoulder external rotation torques as well as a faster ball speed in male pitchers playing on a competitive baseball team. The present findings suggest that suppressing trunk rotation could increase the ball speed but may also increase elbow and shoulder torques among pitchers who demonstrate trunk rotation after foot contact. Assessment of normalised trunk rotation velocity may be a good way to quantify the timing of trunk rotation that accounts for the overall length of the pitching motion.

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DISCLOSURE STATEMENT

No potential conflicts of interest were reported by the authors.

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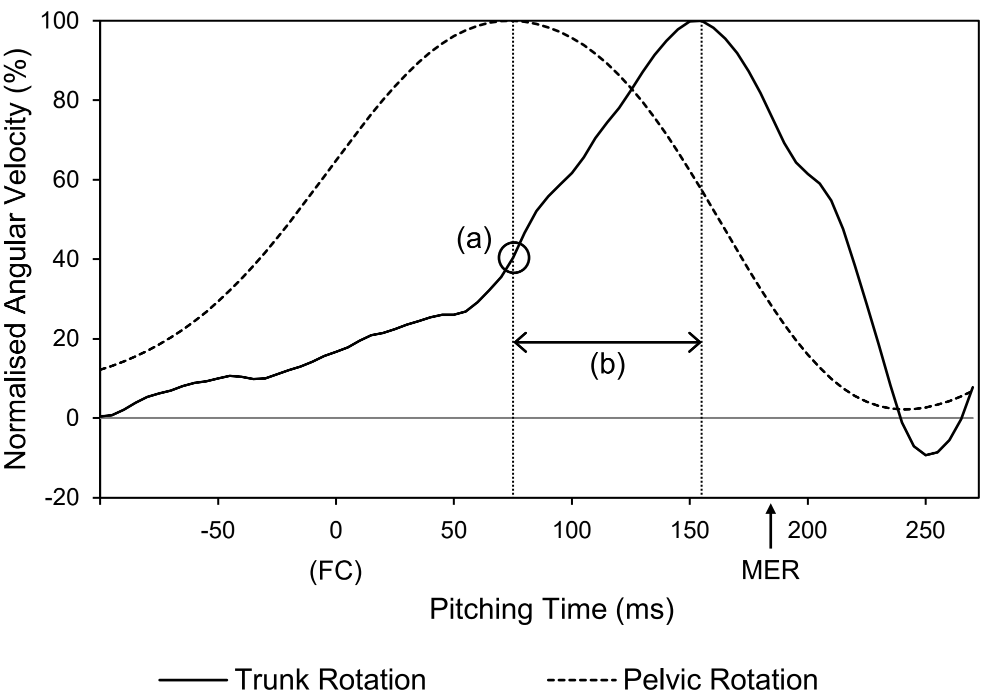
Table 1 Characteristics of participants (N = 18)

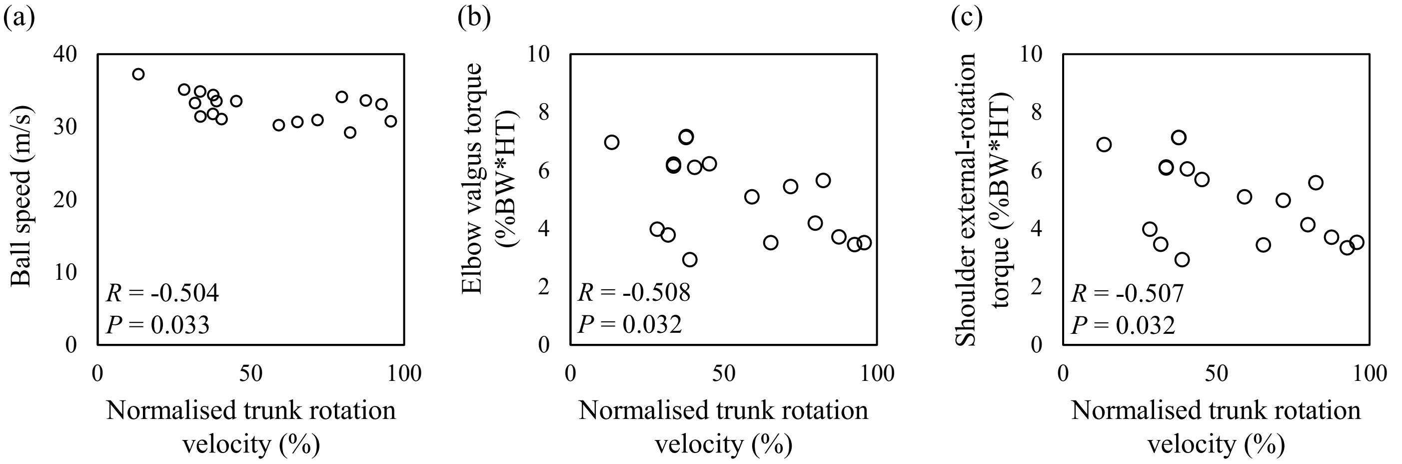
Characteristic	Value
Age, years	21.7 (1.2)
Height, cm	174.7 (6.1)
Mass, kg	73.2 (7.7)
Pitcher experience, years	7.9 (3.5)
Throwing hand (right), N (%)	16 (89%)
Ball speed, m/s	32.7 (2.0)
Peak elbow valgus torque, %BW*HT	5.1 (1.4)
Peak shoulder external rotation torque, %BW*HT	5.0 (1.4)
Normalised trunk rotation velocity at the peak pelvic rotation velocity, %[a]	54.2 (24.7)
Length of time from the peak pelvic rotation velocity to the peak trunk rotation velocity, ms	63.8 (31.7)
Onset of trunk rotation, %[b]	51.8 (10.9)

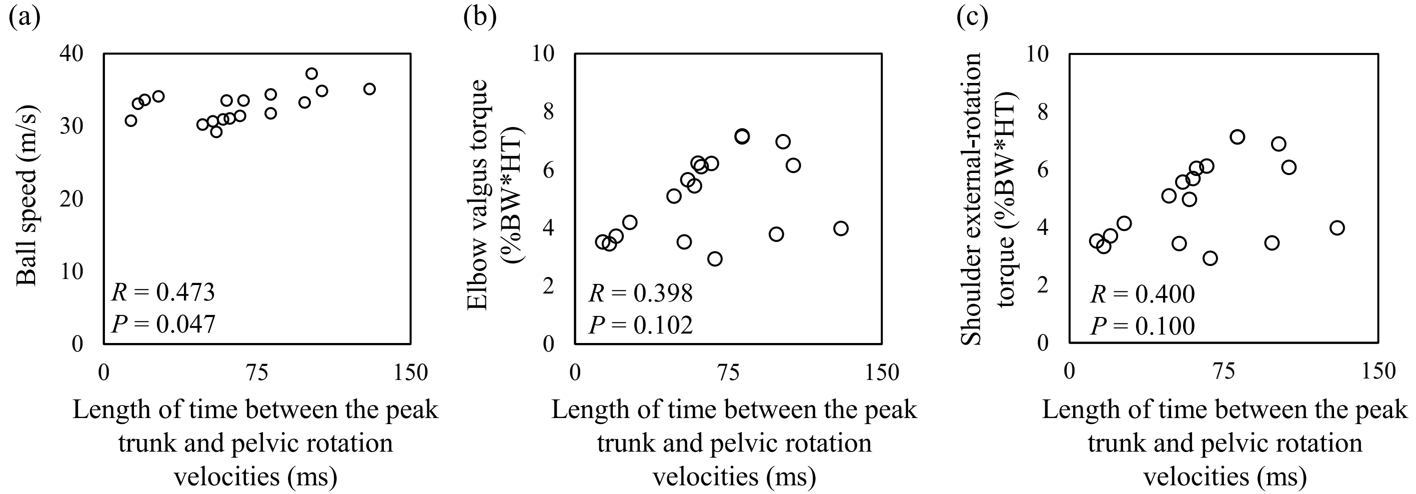
[a]Relative to the peak trunk rotation velocity

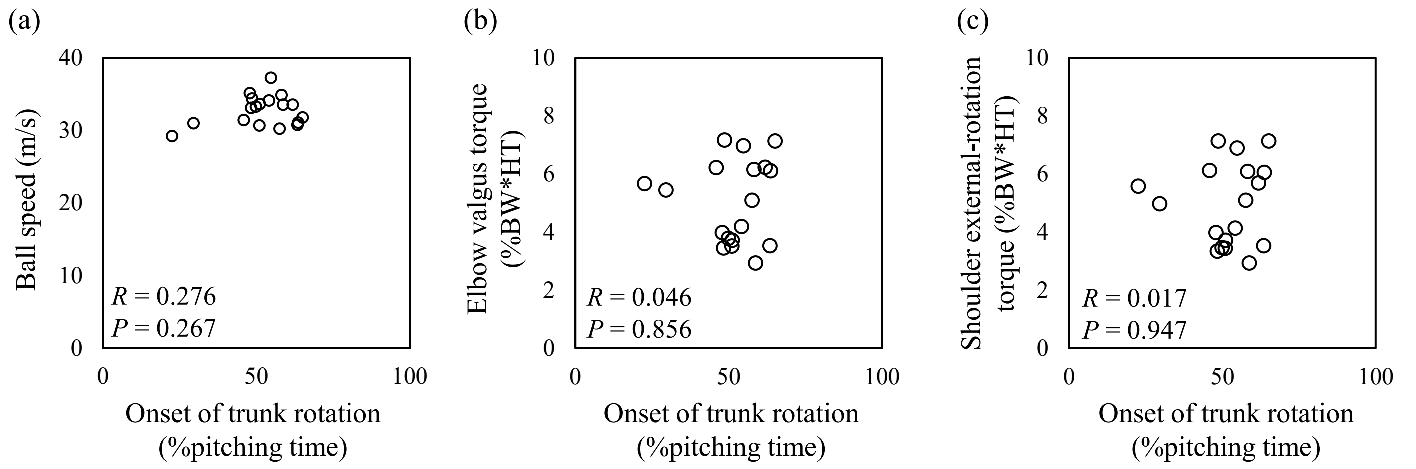
[b]Relative to the pitching time



Normalised Angular Velocity (%)
100
80
60
40
20
0
-20
-50
0
50
100
150
200
250
(FC)
MER
Pitching Time (ms)
(a)
(b)
Trunk Rotation
Pelvic Rotation


(a)
Ball speed (m/s)
40
30
20
10
0
R = -0.504
P = 0.033
0
50
100
Normalised trunk rotation velocity (%)
(b)
Elbow valgus torque (%BW*HT)
10
8
6
4
2
0
R = -0.508
P = 0.032
0
50
100
Normalised trunk rotation velocity (%)
(c)
Shoulder external-rotation torque (%BW*HT)
10
8
6
4
2
0
R = -0.507
P = 0.032
0
50
100
Normalised trunk rotation velocity (%)


(a)
Ball speed (m/s)
40
30
20
10
0
R = 0.473
P = 0.047
0
75
150
Length of time between the peak trunk and pelvic rotation velocities (ms)
(b)
Elbow valgus torque (%BW*HT)
10
8
6
4
2
0
R = 0.398
P = 0.102
0
75
150
Length of time between the peak trunk and pelvic rotation velocities (ms)
(c)
Shoulder external-rotation torque (%BW*HT)
10
8
6
4
2
0
R = 0.400
P = 0.100
0
75
150
Length of time between the peak trunk and pelvic rotation velocities (ms)



(a)
Ball speed (m/s)
R = 0.276
P = 0.267
Onset of trunk rotation (%pitching time)
(b)
Elbow valgus torque (%BW*HT)
R = 0.046
P = 0.856
Onset of trunk rotation (%pitching time)
(c)
Shoulder external-rotation torque (%BW*HT)
R = 0.017
P = 0.947
Onset of trunk rotation (%pitching time)