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Original Article

Biomechanical analysis of the pitching characteristics of adult amateur baseball pitchers throwing standard and lightweight balls

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Abstract. [Purpose] The purpose of this study was to determine the relationship between pitching weight and pitching mechanics, including ball reaction force (BRF) and temporal parameters, for the prevention of throwing injury in adult amateur pitchers. [Participants and Methods] Twenty adult male amateur pitchers (mean age, height, and body mass: 26 ± 3.4 years, 1.7 ± 0.03 m, and 71.6 ± 9.5 kg, respectively) randomly pitched light (110 g) and heavy (145 g) baseballs at maximum velocity. Kinematic, kinetic, and temporal parameters were compared between the light and heavy balls. [Results] Pitching heavy balls significantly increased the BRF to 9.2 N and maximum trunk rotation angular velocity to 26.2°/sec, and decreased the ball speed to 1.4 m/sec and upper limb joint torque efficiency and shoulder internal rotation angular velocity at the moment of ball release at 250.8°/sec. Furthermore, the peak temporal kinetic parameters until ball release appeared early in the throwing of the heavy ball. [Conclusion] Adult amateur pitchers who pitched heavy balls had greater BRF; had decreased upper limb joint torque efficiency, ball speed, and arm angular velocity; and reached maximum kinetics early. Adult amateur pitchers may be at risk of throwing injuries due to throwing of heavy balls.
Key words: Baseball pitching, Adult amateur, Ball weight and biomechanics

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INTRODUCTION

The mechanics involved when youth[1, 2], high school and college[3–5] students pitch balls of various weights have recently been investigated to clarify injury risk and training effects. However, the impact of different ball weights on pitching mechanics in amateur pitchers has not been investigated. The injury rate of Canadian baseball players including amateurs in 1998 was 9% and is 6th among all sports[6]. Given this amateur baseball failure rate, prevention of throwing injury would be important for adult amateur pitchers as well. The current weight of amateur baseball in use in Japan is 138 g, which is lighter than the 145 g of high school, college and professional baseball. Also, the ball weight for amateur baseball was revised in 2018, weighing 2 g heavier than the previous 136 g. Is the recent trend of increasing ball weight in Japanese amateur baseball reasonable from the viewpoint of injury prevention? To examine this question, it is necessary to determine how changes in ball weight affect the pitching motion mechanics of amateur baseball players.

The throwing load during baseball pitches increases risk of upper extremity injury throughout the developmental stages[7–10]. Excessive joint moments in the upper extremities result in throwing injury. Indeed, elbow varus (EVT) and shoulder internal rotation (SIRT) torque is greater in professional players with, than without elbow injury[11]. Factors associated with excessive joint loads include ball speed[12] and maximum shoulder external rotation (MER)[13–15] and shoulder horizontal abduction[15] angles. However, the causative mechanics that directly act upon the shoulder and elbow joints could not be determined, because the distance on the time axis between joint torque and related factors is notable (for example, cor-

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relations between maximum EVT and MER angle). In a study of the association between pitching load and simultaneous parameters, the reaction force of the force applied from the pitcher to the ball (ball reaction force; BRF) had the greatest effect on the maximum torque (EVT, SIRT)[16]. During a baseball pitch, the ball is accelerated from the pitching mound to the home base. Therefore, the BRF is a force from home base in the direction of the pitching mound opposite to the direction of ball acceleration. The value of BRF should be included in the investigation when studying the mechanism of pitching motion in baseball. The effect of different ball weights on the temporal parameters during the pitching motion has not been studied so far and this should also be investigated.

The objectives of this study were 1) to determine the relationship between ball weight and pitching mechanics based on parameters including ball reaction force values in adult amateur pitchers, 2) to determine how differences in ball weight affect temporal parameters during the pitching motion, and then to consider the relationship between differences in ball weight and throwing injury.

PARTICIPANTS AND METHODS

Twenty adult amateur pitchers (mean age, height and body mass: 26 ± 3.4 years, 1.7 ± 0.03 m and 71.6 ± 9.5 kg, respectively) were recruited for this study and all used an overthrow or three-quarter pitching style. Fourteen and six pitchers were right- and left-handed, respectively. All were amateurs with a minimum of two years of pitching experience in high school or college. The exclusion criteria comprised a history of traumatic shoulder or elbow injury, surgery, or current shoulder or elbow pain while throwing. The experiment was conducted according to the Declaration of Helsinki and the Clinical Research Ethics Committees at Gunma University approved the study (approval code 13-48), and all players provided written, informed consent before participating in the study.

We obtained medical and pitching histories from the participants. After stretching and warming up until they felt ready to throw normally, reflective markers were secured onto anatomic landmarks as described.16 They then pitched light (110 g) and heavy (145 g) fastballs five times into a netted target with a designated strike zone. Ball weights of 110 g (approximately 4 oz) and 145 g (approximately 5 oz) were selected, referring to the research that investigated the effect of different ball weights on pitching motion mechanics in youth baseball pitchers[2]. The order of ball weights was randomized for each participant. We analyzed only the fastest of the five pitches.

Pitching motion data were captured using a Vicon 612 3D motion capture system (Vicon Motion Systems Ltd., Yarnton, UK) with 10 cameras (250 Hz). Three-dimensional positional data were filtered using a fourth-order, zero-lag Butterworth filter with a cutoff frequency of 13 Hz[17]. The throwing shoulder and elbow joint centers were calculated as described[16]. The midpoint of the two markers attached to the baseball was defined as the center of the ball. Ground reaction forces of the lead foot during pitching were collected using a 1,000-Hz force plate (AMTI, Watertown, MA, USA) electronically synchronized to motion data.

The pitching motion was divided into six phases as defined[18]. The analytical range of the present study was limited to the arm-cocking phase (lead foot contact [FC] to shoulder MER), arm-acceleration phase (MER to ball release [BR]) and follow-through. Stride-foot contact was identified as the instant when the vertical ground-reaction force from the stride foot exceeded 10 N[19, 20]. Ball release was defined as the instant when the distance between the center of the ball and the marker on the third metacarpal exceeded 15 cm.

Kinematic and kinetic parameters were calculated by modeling the body as a system of rigid segments, as describe[16]. The kinematic assessment included ball speed, angles and angular velocities of the trunk (forward tilt/posterior tilt, lateral tilt, and rotation), the shoulder (external/internal rotation, abduction/adduction, and horizontal adduction/abduction), and elbow (extension/flexion) at the instant of SFC, MER and BR (Fig. 1). Furthermore, maximum angular velocity was analyzed during each pitching cycle. Angular velocity parameters were determined using the five-point central difference method for first derivatives. Ball velocity and acceleration calculated using the same method as the ball center and ball velocity at BR, was considered as ball speed.

The kinetic assessment included SIRT, and EVT of the throwing arm at the instant of SFC, MER and BR. Joint torque parameters were calculated as described[16]. The mass of the light and heavy balls was set to 0.11 and 0.145 kg respectively. Furthermore, SIRT and EVT were divided by ball speed to measure pitching efficiency. These ratios indicate the amount of stress that the shoulder and elbow experience for a given amount of pitch velocity generated (a higher value means lower efficiency)[21]. The BRF was calculated in terms of ball acceleration multiplied by ball mass.

To describe the temporal parameters (maximum EVT, maximum SIRT, MER, maximum BRF, maximum elbow extension angular velocity, maximum shoulder internal rotation velocity), the data were normalized to the total pitch time (from SFC 0% to BR 100%) and are expressed as ratios (%) of pitch times.

Data were statistically analyzed using IBM SPSS Statistics (Version 26) for Mac. Kinematic, kinetic, temporal parameters were compared between light and heavy balls using paired t-tests. Two-tailed p values <0.05 were considered statistically significant.

RESULTS

The speeds of pitched light and heavy balls were 31.4 ± 3.3 and 30 ± 3.4 m/sec, respectively ($p<0.001$). The kinematic parameters of shoulder abduction angle at MER (Table 1), shoulder horizontal adduction at SFC, shoulder internal rotation angular velocity at BR and trunk rotation angular velocity (Table 2) differed significantly between light and heavy pitched

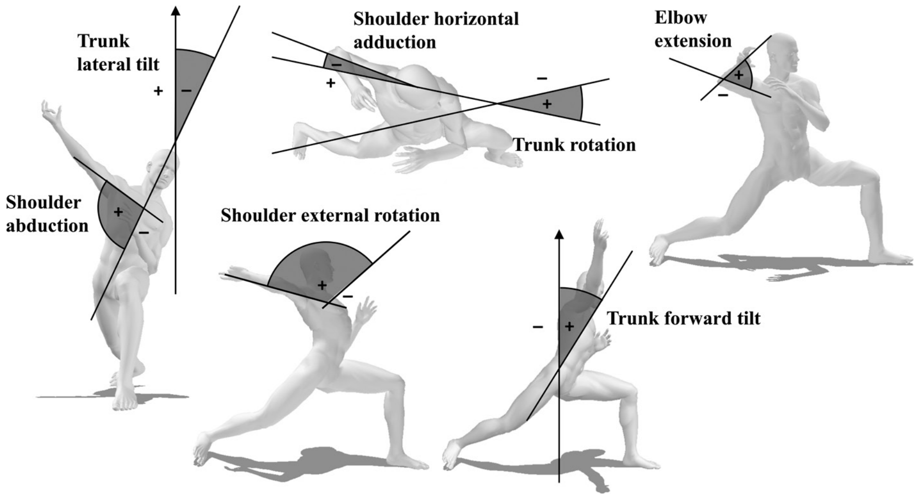

Fig. 1. Definition of joint angle.

Table 1. Comparison between light and heavy weight balls in joint angles (degrees)

	Light weight ball	Heavy weight ball	p-value
Stride foot contact			
Elbow extension	77.8 ± 21.0	77.3 ± 19.5	0.590
Shoulder abduction	70.9 ± 17.0	72.1 ± 18.0	0.346
Shoulder horizontal adduction	−25.4 ± 13.3	−25.9 ± 16.1	0.301
Shoulder external rotation	33.1 ± 29.5	31.0 ± 32.8	0.477
Trunk rotation	26.8 ± 8.6	26.9 ± 7.8	0.816
Trunk forward tilt	−3.7 ± 5.1	−3.3 ± 5.5	0.394
Trunk lateral tilt	3.5 ± 8.3	3.0± 8.0	0.622
Maximum external rotation			
Elbow extension	88.7 ± 16.3	87.9 ± 17.0	0.498
Shoulder abduction	94.6 ± 10.3	95.8 ± 10.1	0.022*
Shoulder horizontal adduction	11.7 ± 8.1	12.7 ± 9.0	0.305
Shoulder external rotation	146.2 ± 13.3	146.9 ± 14.9	0.271
Trunk rotation	−2.3 ± 6.5	−3.0 ± 6.6	0.170
Trunk forward tilt	17.8 ± 7.2	18.5 ± 6.7	0.248
Trunk lateral tilt	−16.5 ± 7.4	−17.1 ± 7.1	0.095
Ball release			
Elbow extension	150.3 ± 7.4	149.2 ± 8.8	0.176
Shoulder abduction	94.2 ± 9.2	94.7 ± 9.3	0.293
Shoulder horizontal adduction	10.5 ± 8.6	11.5 ± 9.6	0.303
Shoulder external rotation	98.3 ± 12.8	101.1 ± 14.4	0.171
Trunk rotation	−13.8 ± 7.6	−15.0 ± 7.8	0.062
Trunk forward tilt	26.7 ± 7.9	27.4 ± 7.9	0.299
Trunk lateral tilt	−23.4 ± 8.2	−24.2 ± 7.7	0.076

*$p<0.05$; data are mean ± SD.

balls.

Among the kinetic parameters, BRF differed significantly between the light and heavy balls. Although shoulder and elbow torque did not significantly differ, torque efficiency was significantly larger for the heavy ball (Table 3).

Among the temporal parameters, maximum BRF timing significantly moved forward as ball mass increased, and the trends for other kinetic parameters until BR were similar (Table 4). In contrast, maximum shoulder internal rotation angular velocity was significantly later when pitching the heavy ball (Table 4).

Table 2. Comparison between light and heavy weight balls in angular velocities (degree/sec)

		Light weight ball	Heavy weight ball	p-value
Stride foot contact				
	Elbow extension	−204.1 ± 208.1	−208.6 ± 217.8	0.893
	Shoulder abduction	133.4 ± 143.9	134.8 ± 150.3	0.929
	Shoulder horizontal adduction	138.8 ± 186.0	142.3 ± 189.5	0.016*
	Shoulder external rotation	752.4 ± 293.1	762.1 ± 265.3	0.771
	Trunk rotation	96.2 ± 98.8	87.2 ± 105.9	0.496
	Trunk forward tilt	91.6 ± 55.5	96.5 ± 57.3	0.258
	Trunk lateral tilt	−148.4 ± 64.2	−151.1 ± 62.0	0.636
Maximum external rotation				
	Elbow extension	1,212.1 ± 362.7	1,176.5 ± 393.7	0.400
	Shoulder abduction	−82.1 ± 141.0	−84.9 ± 147.7	0.867
	Shoulder horizontal adduction	205.2 ± 116.2	198.0 ± 123.7	0.896
	Shoulder external rotation	−4.8 ± 22.0	−5.1 ± 25.8	0.961
	Trunk rotation	−468.1 ± 136.0	−488.7 ± 128.1	0.097
	Trunk forward tilt	242.4 ± 50.4	240.0 ± 55.3	0.635
	Trunk lateral tilt	−159.4 ± 80.0	−157.0 ± 78.2	0.586
Ball release				
	Elbow extension	960.4 ± 472.6	1,056.1 ± 484.7	0.186
	Shoulder abduction	109.9 ± 166.2	96.9 ± 161.1	0.281
	Shoulder horizontal adduction	−7.8 ± 196.9	−19.1 ± 195.4	0.443
	Shoulder external rotation	−4,051.0 ± 1,032.6	−3,800.2 ± 1046.4	0.036*
	Trunk rotation	−116.6 ± 117.8	−74.8 ± 167.0	0.269
	Trunk forward tilt	217.5 ± 55.1	233.3 ± 101.2	0.448
	Trunk lateral tilt	−193.9 ± 55.7	−204.8 ± 78.4	0.269
Maximum value				
	Elbow extension	2,042.9 ± 281.1	2,012.6 ± 269.2	0.280
	Shoulder abduction	373.4 ± 165.7	384.4 ± 172.7	0.429
	Shoulder horizontal adduction	433.3 ± 115.5	440.8 ± 215.9	0.650
	Shoulder external rotation	−4,634.5 ± 1,032.6	−4,517.5 ± 124.4	0.195
	Trunk rotation	−504.5 ± 136.6	−530.7 ± 119.7	0.028*
	Trunk forward tilt	259.7 ± 52.1	277.2 ± 93.7	0.397
	Trunk lateral tilt	−219.2 ± 59.8	−229.1 ± 76.2	0.306

*p<0.05; data are mean ± SD.

Table 3. Comparison between light and heavy weight balls in kinetic parameters

	Light weight ball	Heavy weight ball	p-value
Ball reaction force (N)	42.77 ± 6.42	52.00 ± 8.60	<0.001**
Elbow varus torque (Nm)	42.72 ± 10.42	42.92 ± 10.44	0.801
Shoulder internal rotation torque (Nm)	47.22 ± 10.60	46.27 ± 10.79	0.245
Elbow varus torque efficiency (Nm/ball speed)	1.35 ± 0.23	1.41 ± 0.24	<0.001**
Shoulder internal rotation torque efficiency (Nm/ball speed)	1.49 ± 0.22	1.53 ± 0.22	0.032*

*p<0.05, **p<0.01; data are mean ± SD.

Table 4. Comparison between light and heavy weight balls in temporal parameters (%pitching cycle)

	Light weight ball	Heavy weight ball	p-value
Maximum elbow varus torque	75.45 ± 4.75	74.55 ± 5.05	0.251
Maximum shoulder internal rotation torque	78.00 ± 4.58	77.20 ± 4.93	0.192
Maximum shoulder external rotation angle; MER	79.15 ± 4.22	79.00 ± 4.78	0.837
Maximum ball reaction force	89.90 ± 2.43	87.75 ± 5.12	0.040*
Maximum elbow flexion angular velocity	91.60 ± 2.85	91.90 ± 3.52	0.445
Maximum shoulder internal rotation angular velocity	104.90 ± 2.12	105.69 ± 2.19	0.007**

*p<0.05, **p<0.01; data are mean ± SD.

DISCUSSION

The main findings of this study were that adult amateurs who pitched heavy baseballs increased BRF and decreased ball speed, EVT efficiency and SIRT efficiency with little effect on joint angle, increased shoulder internal rotation angular velocity at BR and maximum trunk rotation. The timing of the maximum value of temporal kinetic parameters until BR had been accelerated.

The speed of a pitched heavy ball decreased (mean difference=1.4 m/sec) as shown by others[1–3]. Neither EVT nor SIRT differed significantly. These results are consistent with the findings of skeletally mature[3], but inconsistent with immature[1, 2] pitchers. Adult mature pitchers might not be susceptible to ball weight because they have heavy segment weights. On the other hand, the torque efficiency of EVT and SIRT was significantly low (mean difference in ball speed, 0.06 and 0.04 Nm, respectively) when pitching a heavy ball, which might have been caused by a greater BRF (mean difference, 9.23 N). Even if throwers have the same power, resulting ball speed is decelerated by a greater BRF working in the opposite direction. The high torque efficiency for a given velocity of a pitched light ball might decrease the amount of cumulative microtrauma that develops in the shoulders and elbows of pitchers over years of pitching[21].

Joint angles differed little and were similar to previous findings[1–3]. Only the shoulder abduction angle at MER was greater when pitching the heavy ball. Studies of pitching mechanics have shown that decreased shoulder abduction angles result in greater upper extremity joint loads[22, 23], low pitching efficiency[17] and injury risk[24] Because these reports did not describe the shoulder abduction angle at MER, and although difficult to adapt directly to our findings, a greater shoulder abduction angle while pitching a heavy ball might compensate for low pitching efficiency and reduce injury risk. Although shoulder internal rotation angular velocity at BR was significantly low (mean difference=250.8 deg/sec), maximum values did not significantly differ. This finding tended to be the same as those in high school and college pitchers[3], but were inconsistent with those for adolescents[2]. This tendency might be caused in the same manner as those of EVT and SIRT. Decreased shoulder internal rotation angular velocity at BR when pitching a heavy ball was a probably due to a greater BRF. Because peak BRF appears at the midpoint between MER and BR[16], a difference in ball weight might affect pitching mechanics during these phases. Indeed, although the difference was not significant, the shoulder external rotation angle at BR was greater by approximately 3 degrees when pitching a heavy ball. This mechanism caused by the BRF might be a power source of inertial lag, which is when the forearm as a proximal segment is rotated towards the opposite direction to throwing[25, 26]. This force may affect the shoulder joint external rotation angle and shoulder joint internal rotation velocity, especially during the MER to BR phase when the BRF reaches its maximum value. Maximum trunk rotation angular velocity was significantly greater (mean difference=26.2 deg/sec) when pitching a heavy ball. Greater trunk rotation angular velocity is related to faster ball speed[27, 28]. Cohen et al. demonstrated that ball speed increases by 0.7 m/sec for every 100 deg/sec increase in trunk rotation angular velocity[28]. Greater trunk rotation angular velocity might be a strategy for preventing the reduction in ball speed imposed by a heavier ball.

The impact of different ball weights on temporal parameters has not been investigated until now. The kinetic parameters (EVT, SIRT) tended to reach a maximum slightly earlier when pitching heavy, rather than light balls. The BRF timing was significant earlier (mean difference, 2.15%) for the heavy ball. These forward effects of kinetic parameters were characteristic of motions when pitching a heavy ball. On the other hand, maximum shoulder internal rotation angular velocity was significantly delayed (mean difference, 0.79%) when pitching a heavy ball. While it is clear that changes in ball weight affect temporal parameters during the pitching motion, it is unclear how these changes affect the risk of throwing injury and further investigation is needed.

This study has some limitations. All balls were pitched on flat ground. The presence or absence of a pitching mound affects pitching kinematics and kinetics[29, 30]. We did not analyze lower extremity kinematics and kinetics. The lower extremities play an important role in pitching[31], therefore, correlations between ball weight and lower extremity mechanics should be analyzed. Only two conditions were used, 110 and 145 g ball weight, and it is not known whether the results of this study can be adapted when using heavier or lighter balls. Previous studies using ball weights of 3 to 6 oz have reported a linear proportional relationship between ball weight and elbow torque, arm speed, and ball speed[1], so some adaptation may be possible, but further investigation is needed.

In conclusion, pitching a heavy ball caused greater BRF, decreased upper limb joint torque efficiency, decreased ball speed, decreased arm angular velocity, and maximum kinetics were reached early. The BRF might correlate with changes in kinetics, kinematics and temporal parameters according to different ball weights. Adult amateur pitchers are at risk of throwing injury resulting from pitching heavier balls.

Presentation at a conference

Part of this study was presented in a poster at ISEK 2020 Virtual Congress (https://isek.org/wp-content/uploads/2020/07/ISEK-Poster-Abstract-Booklet-Jul7.pdf).

Funding and Conflict of interest

The authors have no conflicts of interests to declare.

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