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Article

Relationship between pitching mechanics and biomechanical efficiency of college baseball pitchers

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Abstract: Biomechanical efficiency of baseball pitch is considered to be a better indicator for evaluating pitching skills. Since there is a relationship between elbow varus and elbow mechanics during the arm cocking phase, we attempted to include this variable in the multiple regression analysis to improve the understanding of the biomechanical efficiency of baseball pitching. The fastest pitching of 68 college baseball pitchers was used for analysis. The regression results showed that maximum elbow flexion angle (β: −2.615, p: 0.003), shoulder external rotation angle at the moment of maximum external rotation (MER) (β: 2.881, p: 0.004), maximum trunk rotation velocity (β: −0.333, p: 0.001), trunk rotation angle at the moment of stride foot contact (SFC) (β: −2.031, p:0.006), time between maximum pelvic rotation velocity and maximum trunk rotation velocity (β: 1.238, p: 0.023), and shoulder abduction angle at the moment of SFC (β: −2.048, p: 0.033) correlated with biomechanical efficiency and explained 45% of the variance in biomechanical efficiency. Therefore, further improvements in elbow mechanics during the arm cocking phase, based on improvements in early pitching mechanics, may help to increase pitching velocity per unit of elbow varus torque.

Keywords: biomechanical efficiency; varus torque; elbow injury; biomechanical performance

1.Introduction

Elbow injuries are a prevalent concern in baseball, affecting players at all levels and often leading to significant time away from the game or even surgical interventions [1–3]. These injuries can severely impact an athlete's career, making it crucial to understand their underlying causes. The primary mechanism behind elbow injuries is excessive loading on the joint, typically resulting from poor pitching mechanics. Specific mechanical faults, such as premature trunk rotation before the stride foot contacts the ground and excessive contralateral tilting of the trunk, have been implicated in increasing the risk of injury [4,5].

During the pitching motion, the elbow experiences valgus torque, which places considerable stress on the medial aspect of the elbow joint. This stress results in large tensile forces that can lead to injury if not properly managed. To counteract this external load, the ulnar collateral ligament (UCL) and the wrist flexors generate a corresponding varus torque, representing the internal load on the elbow [6–8].

Biomechanically, the elbow is a complex joint that relies on a delicate balance of forces and movements. The muscles, tendons, and ligaments surrounding the elbow work in harmony to enable smooth and efficient movement. For example, the biceps brachii and triceps brachii play key roles in elbow flexion and extension, respectively.

Their coordinated contractions and relaxations are essential for proper pitching mechanics. Additionally, the rotator cuff muscles in the shoulder, which are closely linked to elbow function, contribute to the overall stability and force transmission during the pitching motion [9].

Consequently, the varus torque experienced by the elbow has been identified as a significant predictor of elbow injuries in pitchers. Despite extensive research on elbow injuries in baseball, recent epidemiological data indicate a worrying trend: the incidence of UCL injuries is on the rise among youth and collegiate pitchers [10]. Therefore, it is imperative to elucidate how modifications in pitching mechanics can influence both injury risk and athletic performance.

In recent years, researchers have introduced the concept of "biomechanical efficiency" as a more nuanced measure of pitching mechanics [11–13]. Biomechanical efficiency refers to the ability to achieve greater output, specifically pitching velocity, with less input, such as joint kinetics. This efficiency is quantified by dividing the ball velocity by the normalized elbow varus torque; higher values indicate greater biomechanical efficiency.

From a broader biomechanical perspective, the kinetic chain in pitching is a complex sequence of movements that starts from the lower body and progresses through the trunk, shoulder, and finally the elbow and wrist. Each segment of the kinetic chain contributes to the overall power and accuracy of the pitch. For instance, a strong and stable base provided by the lower body allows for efficient transfer of energy up the chain. The rotation of the hips and trunk generates torque, which is then transmitted to the upper body. The shoulder serves as a crucial link in this chain, providing mobility and stability while also contributing to the generation of force. Any disruption or inefficiency in this kinetic chain can lead to increased stress on the elbow and a higher risk of injury [14]. Previous studies have demonstrated that effective management of the early phases of the pitching kinetic chain correlates with improved biomechanical efficiency. Key factors include earlier pelvic rotation, trunk rotation following the landing of the stride foot, enhanced energy transfer from the lower limbs, and the optimization of shoulder angles [5,15,16]. However, it is also evident that the elbow flexion angle during pitching plays a critical role in elbow loading [17,18].

The maximum elbow varus torque typically occurs during the arm cocking phase, which spans from stride foot contact to maximal shoulder external rotation. During this phase, the elbow initially flexes before rapidly extending in response to trunk rotation, reaching its peak varus load at the end of the phase [6,19,20]. The angle of the elbow significantly influences the position of the forearm's center of mass and the moment arm for forearm rotation, subsequently affecting the varus torque experienced at the elbow [17]. Biomechanical models have been developed to better understand the complex interactions between the elbow and the rest of the body during pitching. These models use principles of physics, such as Newton's laws of motion, to simulate the forces and movements involved. For example, finite element models can analyze the stress distribution within the elbow joint under different loading conditions, providing valuable insights into the mechanisms of injury [21].

Notably, a study conducted multiple regression analyses to examine biomechanical efficiency using various pitching mechanics as independent variables. However, this analysis did not include elbow mechanics during the arm cocking phase, ultimately explaining only 27% of the variance in biomechanical efficiency [13]. Given the critical importance of elbow mechanics during this phase, it is essential to incorporate these parameters into future research to enhance our understanding of baseball biomechanical efficiency.

The primary objective of this study is to integrate elbow mechanics, specifically the parameters associated with the arm cocking phase, into the regression variables. By doing so, we aim to gain a deeper insight into the relationship between pitching mechanics and elbow varus torque biomechanical efficiency. Furthermore, this research seeks to provide actionable recommendations for improving performance and reducing the risk of injury among college baseball pitchers. We hypothesize that the mechanics of the elbow during the arm cocking phase will exhibit a significant relationship with biomechanical efficiency, and that including this variable will enhance the interpretation of the variance in biomechanical efficiency.

2. Methods

2.1. Participants

Our subject data were obtained from Wasser berger's Open Biome chanics Project database [22]. After excluding poor data we selected data from 68 college baseball pitchers for analysis. Statistical data for all subjects: mean age 20.6 ± 1.3 years, mean mass 88.77 ± 9.11 kg, mean height 1.84 ± 0.07 m, mean pitching speed 38.19 ± 1.92 m/s (85.43 ± 4.29 mph). Western IRB provided ethical approval for all data collection procedures (Western IRB # WB-DLR-115).

2.2. Data collection procedures

All athletes underwent motion capture in the Driveline Baseball Lab, equipped with advanced tools such as force plates and a high-speed motion capture system. They began with a standardized warm-up program that included foam rolling, static and dynamic stretching, resistance band exercises, and specific throwing warm-up routines. Once fully warmed up, the athletes removed any loose clothing and had 47 reflective markers strategically placed on various bony landmarks, as illustrated in **Figure 1**. After the markers were applied, the athletes were given additional warm-up time to acclimate to the markers and practice throwing on the mound.

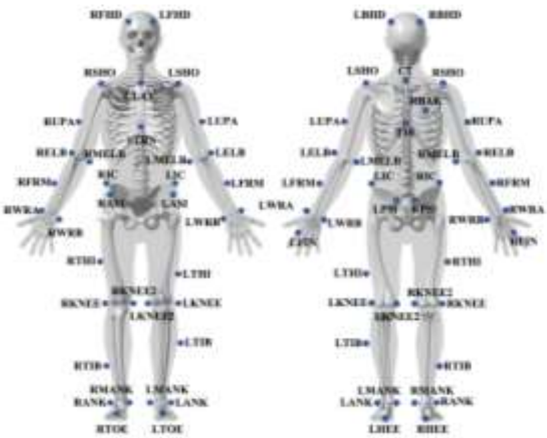

Figure 1. Marker set.

After the athletes indicated that they were sufficiently warmed up, they threw at least five fastballs while a motion capture system consisting of 14 cameras (Natural Point Inc.; Corvallis, OR, USA) and three force plates (Bertec Corp.; Columbus, OH, USA) captured kinematic and kinetic data at 360 HZ and 1080 HZ, respectively. Three force platforms were embedded under the turf pitching surface (thickness = 0.013 meters). One force platform was located under the drive leg to collect data during its windup and stride phases. The other two force plates were located in the pitcher's landing zone (located 1.3 m to 2.2 m in front of the pitching rubber) to collect data after the stride leg landed. The landing zone platform was rotated approximately 4.8 degrees to accommodate the prescribed inclination of the pitcher's mound. Standard motion capture software (Motive 2.2-Motive 3.0; Natural Point Inc, Corvalis, OR, USA) collected and synchronized kinematic and kinetic data. A calibrated radar gun located behind home plate, parallel to the direction of the pitch, was used to capture the speed of the pitch (Stalker Pro II; Stalker Sport; Richardson, TX, USA).

2.3. Data processing procedures.

All the kinematic (**Table 1**) and kinetic data were meticulously processed. Initially, in the Visual3D (C-Motion, Germantown, MD) software, a fourth-order Butterworth lowpass filter was employed. The kinematic data was filtered with a cut-off frequency of 20 Hz, while the kinetic data was filtered at 40 Hz. This approach was consistent with that used in previous studies [17,23,24]. From the collected data, only the fastest pitches with reliable marking data were ultimately selected for in-depth analysis.

A well-defined coordinate system was established to accurately analyze the pitching motion. A global coordinate system was set up, where the *z*-axis was oriented vertically upwards, the *x*-axis pointed towards the home plate, and the *y*-axis was perpendicular to the plane formed by the *x* and *z*-axes. In Visual3D, the pelvic coordinate system was defined using the CODA pelvis (Charnwood Dynamics Ldt., UK). This advanced system automatically generated hip joint centers by utilizing the Bell and Brand regression equations [25]. The trunk model was constructed in strict accordance with the ISB recommendations. The shoulder joint center landmark was created as an offset from the right and left acromion markers [26]. For the ankle, knee, elbow, and wrist joints, their joint centers were precisely defined as the midpoint between the medial and lateral markers, respectively.

Based on previous research [27], the pitching motion was divided into three distinct phases. The stride phase spanned from the maximum stride leg knee height (MKH) to the stride foot contact (SFC) with the ground. The arm cocking phase was defined as the time interval between SFC and the throwing shoulder's maximal external rotation (MER). The arm acceleration phase commenced from MER and ended at ball release (BR). The SFC was determined by a vertical ground reaction force (GRF) of more than 10 N [28]. Ball release was precisely defined as the moment of peak rotation of the hand segment in the global coordinate system [29]. When it came to elbow and shoulder joint angles, the previous anatomical conventions were adhered to [18] (**Figure 2**). Elbow varus torque was normalized as a percentage of body weight in Newtons multiplied by height in meters. Finally, biomechanical efficiency was calculated as the ball velocity per unit of standardized elbow varus torque, providing a comprehensive metric for evaluating the pitching mechanics.

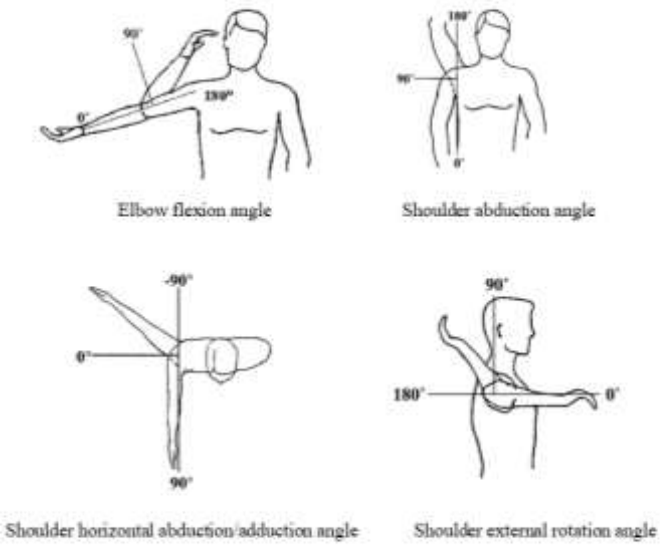

Figure 2. Elbow and shoulder angle conventions.

Table 1. 31 kinematic variables were identified based on previous studies.

categorization	number	parameters(unit)
SFC	1	Step length (% height)
	2	Stride leg knee angle(º)
	3	Trunk longitudinal rotation angle(º)
	4	Pelvic rotation angle(º)
	5	Pelvic rotation angular velocity(º/s)
	6	Trunk rotation angular velocity(º/s)
	7	Shoulder horizontal abduction angle(º)
	8	Shoulder abduction angle(º)
	9	Shoulder external rotation angle(º)
	10	Elbow flexion angle (º)
SFC-MER	11	Elbow max flexion angle(º)
	12	Elbow extension onset time(%PC)
MER	13	Shoulder external rotation angle(º)
	14	Shoulder horizontal abduction angle(º)
	15	Elbow flexion angle(º)
	16	Elbow extension angular velocity(º/s)
BR	17	Stride leg knee angle(º)
	18	Trunk forward flexion angle(º)
	19	Trunk contralateral tilt angle(º)
	20	Shoulder abduction angle(º)

Table 1. (*Continued*).

categorization	number	parameters(unit)
SFC-BR	21	Max pelvis rotational angular velocity (MPAV)(°/s)
	22	Max trunk rotational angular velocity (MTAV)(°/s)
	23	Max shoulder horizontal adduction angular velocity(°/s)
	24	Max shoulder internal rotation angular velocity(°/s)
	25	Max elbow extension angular velocity(°/s)
	26	Stride leg knee excursion angle(°)
TIME	27	SFC to MER (ms)
	28	SFC to MPAV (ms)
	29	SFC to MTAV (ms)
	30	MPAV to MTAV (ms)
	31	Trunk rotation onset time(%PT)

MKH: maximum knee height; SFC: stride foot contact; MER: maximum external rotation; BR: ball release; MAX: maximum. PT: pitch time (SFC is 0%, BR is 100%).

1) Stride length was defined as the vector length of the left and right ankle centers between MKH and SFC, as a percentage of height [30].

2) The maximum elbow flexion angle during the arm cocking phase was defined as the elbow joint angle at the beginning of sustained elbow extension.

3) Elbow extension onset time was defined as the time from SFC to maximum elbow flexion as a percentage of the entire pitching time.

4) Stride leg knee excursion angle is defined as the change in knee flexion angle from SFC to BR [13].

5) The trunk rotation onset time is calculated as the time from foot contact to peak shoulder-pelvic separation as a percentage of the entire pitching time [31].

2.4. Statistical analyses

A comprehensive set of statistical analyses was employed to evaluate the relationship between pitching mechanics and elbow biomechanical efficiency. Initially, a linear stepwise multiple regression analysis was carried out. This aimed to explore the connection between 31 kinematic parameters and biomechanical efficiency, and to pinpoint an optimal set of kinematic parameters capable of jointly predicting biomechanical efficiency. Residual independence was tested using the Durbin Watson test, multicollinearity between the respective variables was tested using the Variance Inflation Factor (VIF), and the normal distributability of the residuals was verified using residual histograms. Then, high and low biomechanical efficiency groups were formed based on the upper and lower 33% distributions of the biomechanical efficiency metrics as in previous studies [13,32]. The significant predictors of multiple regression, determined by the Mann-Whitney U test, were compared between these two groups. All analyses were conducted using SPSS (version 26, IBM, Armonk, NY, USA) a priori with $\alpha = 0.05$.

3. Results

Analysis of the multiple regression showed that six kinematic variables explained 45% of the variance in biomechanical efficiency. An increase in the magnitude of elbow varus torque biomechanical efficiency in college baseball pitchers was associated with: a decrease in the maximum elbow flexion angle, an increase in the MER shoulder external rotation angle, a decrease in the maximum trunk rotation velocity, a decrease in the SFC trunk rotation angle, a decrease in the time of MPVA to MTVA, and a decrease in the SFC shoulder abduction angle (**Table 2**). The Durbin Watson value for the multiple regression: 2.268, all VIF values were less than 1.2, and the standard deviation of the histogram was: 0.954, which indicated that the residuals were consistent with normality and that there was no multicollinearity in the variables.

Height, weight and ball velocity were not significantly different between the high and low biomechanical efficiency groups, but the height *p*-value was equal to 0.05, which was close to being significantly different. Normalised elbow varus torque and biomechanical efficiency were significantly different with *p*-values less than 0.001 (**Table 3**). Regarding the significant variables of the multiple regression, there were significant differences between the maximum elbow flexion angle, the MER shoulder external rotation angle and the SFC shoulder abduction angle between the high and low biomechanical efficiency groups (**Table 3**).

Table 2. Results of multiple linear regressions explaining variance in biomechanical efficiency.

Parameter	Unstandardized Coefficients	Standardized coefficients	*P* value
Max elbow flexion angle	−2.615	−0.302	0.003
MER shoulder external rotation angle	2.881	0.302	0.004
Max trunk rotational velocity	−0.333	−0.339	0.001
SFC trunk longitudinal rotation angle	−2.031	−0.273	0.006
Time MPAV to MTAV	−1.238	−0.225	0.023
SFC shoulder abduction angle	−2.048	−0.219	0.033

$R = 0.671$, $R^2 = 45$. MKH: maximum knee height; SFC: stride foot contact; MER: maximum external rotation; BR: ball release; MAX: maximum; MPAV: Max pelvis rotational angular velocity; MTAV: Max trunk rotational angular velocity.

Table 3. General comparisons between low and high efficiency groups.

Parameter	Low Efficiency (*n* = 22)	High Efficiency (*n* = 22)	*P* value
Height (m)	1.83 ± 0.06	1.87 ± 0.06	0.050
Mass (kg)	87.36 ± 7.86	88.51 ± 11.40	0.723
Ball velocity (m/s)	38.04 ± 1.84	38.34 ± 1.99	0.706
Normalized elbow varus torque (%wt*ht)	0.076 ± 0.005	0.055 ± 0.005	<0.001
biomechanical efficiency (ball velocity/normalized elbow varus torque)	501.8 ± 24.99	697.6 ± 70.77	<0.001
Max elbow flexion angle (º)	119.9 ± 8.7	113.2 ± 11.11	0.047*
MER shoulder external rotation angle (º)	154.2 ± 9.501	171.4 ± 7.11	0.029*
Max trunk rotational velocity (º)	1090 ± 89.03	1049 ± 95.94	0.299
SFC trunk longitudinal rotation angle (º)	−94.99 ± 12.03	−98.74 ± 14.31	0.522
Time MPAV to MTAV	14.82 ± 18.46	6.32 ± 9.55	0.085
SFC shoulder abduction angle (º)	89.19 ± 8.75	83.42 ± 6.4	0.011*

4. Discussion

Elbow mechanics during the arm cocking phase play a crucial role in influencing elbow varus torque. In our study, we sought to incorporate this mechanical parameter into our regression variables to enhance our understanding of throwing mechanics and biomechanical efficiency. The results validated our hypothesis, revealing that our regression model explained 45% of the variance in biomechanical efficiency. This represents a significant improvement, as it is double the explanatory power compared to the 27% of variance explained in the previous study [13].

Relationship of lower extremity, pelvic and trunk mechanics to biomechanical efficiency

Effective management of the early stages of the kinetic chain is considered vital for improving pitching skills. Such management can be modified with guidance from coaches [33]. While previous studies have identified relationships between lower extremity mechanics—such as stride length, knee angle, and knee extension velocity—and elbow loading, our findings did not demonstrate a significant relationship between lower extremity-related mechanics and biomechanical efficiency. We hypothesize that the influence of the lower extremity on elbow loading may be more indirect, primarily affecting trunk mechanics. Additionally, inter-player variability could contribute to these results [10,34,35].

Our regression results indicate that upper body mechanics above the pelvis are the primary factors influencing biomechanical efficiency, which aligns with previous findings [13]. Specifically, the regression analyses revealed that an increase in biomechanical efficiency correlates with a smaller torso angle at the moment of stride foot contact (SFC). It is generally accepted that reduced torso rotation (further away from home plate) at the moment of stride foot touchdown enhances biomechanical efficiency [17]. However, the pelvic angle at SFC did not show a significant effect on elbow pitching mechanics. This contrasts with findings from two previous studies. One study demonstrated that increased pelvic rotation at SFC significantly reduced elbow varus moments, while Crotin et al. found that the high biomechanical efficiency group exhibited less pelvic rotation [13,36]. Furthermore, Sakiko Oyama et al. did not observe significant differences in elbow varus torque among high school baseball pitchers with improper torso rotation sequences [37]. These discrepancies may arise from the different methods employed to assess the order of trunk rotation.

In addition, our regression analyses indicated that a decrease in time from maximal pelvic rotation to maximal trunk rotation is associated with an increase in biomechanical efficiency. This suggests that early pelvic rotation or increased ground reaction forces after foot contact enable the pelvis to achieve maximum velocity more rapidly, allowing the torso to follow the pelvic rotation without significantly reducing the pelvic-torso separation angle. Consequently, initiating rotation as soon as possible after landing to minimize the time between these two events appears beneficial for biomechanical efficiency [38,39]. There may be an optimal moment for torso rotation, as excessive inhibition of torso rotation is thought to increase external loads on the shoulder and elbow joints and decrease ball speed [31,40]. Future research should work toward finding this optimal timing of torso rotation.

Greater torso rotation speed reduces elbow biomechanical efficiency due to the fact that 86% of the energy transferred from the elbow joint is caused by torso flexion and rotation, which accelerates elbow valgus, but the energy generated by excessively high torso rotation may not be efficiently converted from the elbow joint to ball speed. Optimal trunk rotation speed may vary depending on body size and strength of the ligaments, and future studies should be conducted [41].

Relationship between shoulder and elbow mechanics and biomechanical efficiency

Similar to previous studies, a smaller shoulder abduction angle at the SFC moment contributes to biomechanical efficiency [13,18]. With a high biomechanical efficiency shoulder abduction angle of 83º in this study and 86º in the high efficiency group in Ryan L. Crotin's study, and in conjunction with previous research on minimising shoulder loading, we hypothesise that a shoulder abduction angle of less than or in the vicinity of 85º is likely to be the best pitching option [42,43].

Greater shoulder external rotation angle at the MER moment was associated with greater biomechanical efficiency, similar to the findings of the former Ryan L. Crotin study. However, greater shoulder external rotation was also associated with greater elbow varus, as explained by Ryan L. Crotin This greater elbow varus simultaneously increased higher ball velocities, bringing about an increase in biomechanical efficiency[13]. Additionally, a greater shoulder external rotation angle may result in a greater shoulder internal rotation torque, and this internal rotation interaction may minimize external loading on the elbow, thus improving biomechanical efficiency in internal varus [44–46].

In our study, we defined the joint angle at which the elbow joint begins to sustain extension during the arm cocking phase as the maximum flexion angle of the elbow joint. The inclusion of this variable in our regression analyses significantly increased the model's ability to explain differences in biomechanical efficiency, improving from 27% to 45% [13]. This finding supports the widely accepted view among pitching coaches that the elbow should be straighter during the pitching motion [47]. The high-efficiency group displayed a smaller elbow flexion angle than the low-efficiency group. This observation suggests that the elbow joint's initiation of extension at a smaller flexion angle may reduce the interactive effects caused by torso rotation and shoulder horizontal adduction at the end of the arm cocking period. As a result, this allows the elbow joint to experience less external loading [48]. While managing the early phases of the kinetic chain is more accessible for coaches and players to modify, it is crucial to recognize that elbow mechanics after the SFC moment can also significantly impact biomechanical efficiency. Understanding how to control the angle of the elbow joint during the arm cocking phase remains a pertinent issue that warrants further investigation in future research. In conclusion, our findings highlight the intricate relationships between various mechanical factors influencing pitching performance. By focusing on optimizing these mechanics, coaches and players can work towards enhancing biomechanical efficiency and ultimately improving pitching outcomes.

Limitations

This study has several limitations that should be acknowledged. First, the data collected in the laboratory may have influenced the performance of the pitchers, despite their adequate warm-up prior to the experiment to help them acclimatize to the experimental conditions. Additionally, the data were gathered over a period in a single laboratory setting, which means there was no a priori power analysis conducted to determine the sample size's adequacy. Furthermore, due to the inherent complexity of pitching mechanics, it remains uncertain whether our findings can be generalized to pitchers at other levels. Therefore, caution is advised when extending these results to youth or professional pitchers. Future studies should aim to replicate these findings across diverse settings and populations to enhance the applicability and reliability of the results in different pitching contexts.

5. Conclusion

This study incorporated elbow mechanics during the arm cocking phase as a variable in a multiple regression analysis. The findings revealed that six kinematic variables were significantly associated with biomechanical efficiency. Notably, the inclusion of elbow mechanics enhanced the understanding of the variance in biomechanical efficiency. These results suggest that by modifying early pitching mechanics while considering elbow joint mechanics, it may be possible to improve ball velocity. This emphasizes the importance of a holistic approach to pitching technique, focusing on both kinematic and elbow mechanics to optimize performance and reduce injury risk.

Author contributions: Conceptualization, ML, YK and MD; methodology, ML and SK; software, ML and YK; validation, HH and SK; formal analysis, ML, YK and MD; investigation, ML, YK and MD; resources, YK and SK; data curation, YK; writing—original draft preparation, ML, YK and MD; writing—review and editing, MD and SK; visualization, HH and SK; supervision, HH and SK; project administration, YK; funding acquisition, SK. All authors have read and agreed to the published version of the manuscript.

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Ethical approval: The study was conducted in accordance with the Declaration of Helsinki, and was approved by the Ethics Committee of Jeonbuk National University (JBNU2022-01-004-002). All subjects signed an informed consent form before the experiment.

Conflict of interest: The authors declare no conflict of interest.

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