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Sensor-based Motion Analysis for Injury Assessment in Professional Pitchers

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Injury assessment in professional pitchers is critical for optimizing performance and extending athletic careers. In this study, we explore advanced methodologies for evaluating and preventing injuries specific to throwing sports by examining publicly available videos of professional pitchers captured with a high-end broadcast camera system equipped with a CMOS image sensor. (1) Background: In this study, we aim to investigate several key parameters related to upper limb injuries in pitchers. (2) Methods: We conducted 2D motion analysis, assessed pitching mechanics, and applied inverse dynamics to examine seven elite Major League Baseball pitchers. (3) Results: We found that maximum external rotation and stride length are closely related to ball speed. Additionally, the maximum external force and elbow varus torque produced by the baseball exhibit linear relationships with ball speed. These factors contribute significantly to upper extremity injuries. (4) Conclusions: The application of image sensors in broadcast camera systems is crucial for capturing motion parameters in the fast movements of professional pitchers. Optimizing pitching mechanics, particularly in terms of maximum external rotation, stride length, external force, and elbow varus torque, is essential for preventing upper extremity injuries and enhancing performance in pitchers.

1. Introduction

Baseball originated in 19th century England and later spread to North America. After becoming a national sport in the United States, it extended to Central and South America, as well as Eastern Asia.[(1)] However, pitcher injuries have become an epidemic in Major League

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Baseball (MLB). According to the Roster Resource - Injury Report, of the 511 players on MLB teams' injured lists during the 2024 season, 325 were pitchers (nearly 64%).(2) Klawans(3) reported that the situation was even more severe: out of the 166 players who began the 2024 season on an MLB team's injured list, 132 were pitchers, accounting for nearly 80%.

The primary causes of pitcher injuries include the following:

Incorrect Pitching Techniques: Improper techniques can place excessive stress on the shoulder, elbow, and other joints, leading to injuries such as rotator cuff tears, labral tears, flexor tendinitis, and ulnar collateral ligament (UCL) injuries [Fig. 1(4)].

Overuse: Repeated pitching [high pitch counts, limited rest time of 15 to 20 s between pitches as defined by the pitch clock(5)] without adequate rest and pitching at high velocities can result in muscle fatigue and cumulative trauma to the musculoskeletal system, leading to overuse injuries such as tendonitis and stress fractures. It is crucial to recognize that greater fatigue correlates with a higher risk of injury.

Triplet *et al.*(6) conducted a systematic review and meta-analysis of 21 out of 937 articles from PubMed (MEDLINE), the Cumulative Index for Nursing and Allied Health Literature, and the Cochrane Register of Controlled Trials & Cochrane Library. They concluded that elbow torque is affected by proper pitching mechanics, pitch counts, fatigue, and arm slot, with the greatest elbow torque occurring at maximum shoulder external rotation during the late cocking phase of throwing. Cohen *et al.*(7) investigated 99 collegiate pitchers (aged 18.0–24.8 years) and found that an increase in ball speed by 0.6 m/s corresponds to a 2.54 N·m increase in the varus moment of the elbow for every 10° increase in average trunk rotation angle at ball release. This increase in varus moment places additional stress on the elbow's surrounding muscles and the medial collateral ligament. Manzi *et al.*(8) reviewed 24 articles examining 2896 pitchers from The Cochrane Database of Systematic Reviews, the Cochrane Central Register of Controlled Trials, PubMed (2008–2019), and Ovid/MEDLINE (2008–2019). They found that pitch velocity was significantly correlated with elbow varus torque, elbow distraction, and throwing arm injury.

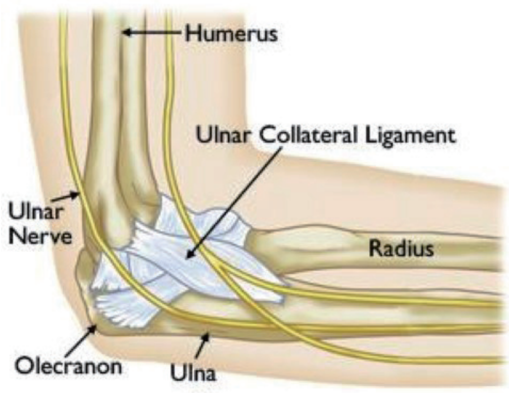

Fig. 1. (Color online) UCL shown from the side closest to the body.(4)

Many articles also examine UCL injuries, including UCL reconstruction (commonly known as Tommy John Surgery), risk factors and prevention, biomechanics and rehabilitation, and nonsurgical treatments.(9–13) Tommy John was the first recipient of UCL reconstruction surgery in 1974. According to the Tommy John Surgery Tracker,(14) a total of 2473 athletes had received this surgery by 2024. Bullock *et al.*(15) found that initial lower extremity or trunk injuries increase the subsequent risk of arm injuries by examining 297 participating pitchers. Recker *et al.*(16) reviewed nine studies involving 159 professional baseball players and concluded that pitchers with latissimus dorsi and teres major tendon injuries have a high rate of return to play after either operative or nonoperative treatment.

Pitchers play a crucial role in determining the outcome of baseball games. A skilled pitcher possesses formidable suppression power and is often considered the backbone of the team. Excellent pitchers are highly sought after, with their performance judged on the basis of criteria such as ball speed, pitching strategy, and control. The overhead throwing motion is a complex display of full-body coordination, requiring smooth and synchronized muscle actions to enhance both velocity and accuracy.

Pitching can be divided into six phases: initial motion (wind-up), balance point (knee up), stride foot contact, maximum external rotation (max ER, arm acceleration), ball release (arm deceleration), and maximum internal rotation (follow-through), as illustrated in Fig. 2.(17)

Numerous studies focus on pitcher movements. Mine *et al.*(18) performed a meta-analysis by reviewing 29 descriptive biomechanical studies from eight English and Japanese language databases. Their subgroup analyses revealed that professional pitchers exhibit significantly higher stride length, peak shoulder internal rotation velocity, peak shoulder proximal force, and ball velocity than collegiate pitchers. Calcei *et al.*(19) reviewed 88 studies and highlighted a notable impact of upper extremity rotational kinetics on the risk of shoulder injury. Contributing factors include the lead leg's position upon landing, the degree of knee flexion, the timing and alignment of trunk rotation, and

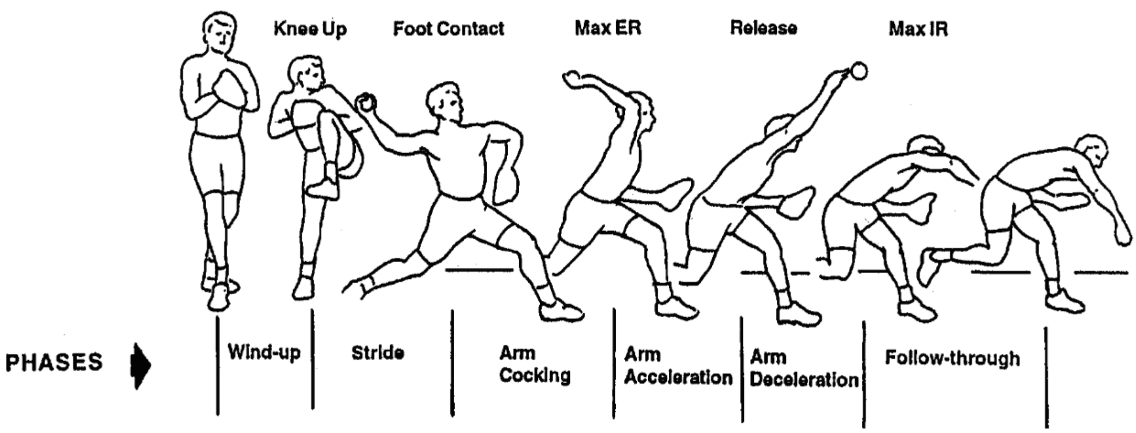

Fig. 2. Six phases of pitching.(17)

the shoulder's range of motion and positioning. Shibata *et al.*[20] investigated the throwing mechanics of fastball pitching in seven pitchers, focusing on controlling the ball spin rate through synergistic joint torque. They used the inverse dynamics method to calculate the kinematics and kinetics of the fingers, wrist, elbow, and shoulder. Fronek and Qadeer[21] discussed baseline motion analysis related to the pitcher's age, workload, conditioning, and genetic factors, and emphasized the need for evaluation before injury. Machado *et al.*[22] surveyed sixty-five studies and found that athletes with shoulder complaints performed worse in trunk stability and endurance tests. Athletes with high throwing performance showed better results in countermovement jumps, horizontal jumps, power measures, and knee extension strength. Laudner *et al.*[23] evaluated 43 pitchers and demonstrated a relationship between the lumbopelvic control of the drive leg and both shoulder horizontal torque and elbow valgus torque during the throwing motion. Owing to these relationships, clinicians should consider incorporating lumbopelvic control training exercises to minimize the kinetic forces on the throwing shoulder and elbow during pitching.

Many researchers investigated the movement of pitchers via cameras and motion-capture devices equipped with infrared light sources, CMOS image sensors, and remote controllers. Manzi *et al.*[24] investigated 91 out of 323 professional baseball pitchers who threw 8–12 fastball pitches while being evaluated with 3D motion-capture technology (480 Hz). They created a linear mixed model with random intercepts to assess ball velocity as a predictor of peak kinetic values when comparing pitches within an individual pitcher. Manzi *et al.*[25] explored the effect of varying chronological orders of maximum joint and segment velocities on ball velocity and upper extremity kinetics by assessing 287 professional baseball pitchers with 3D motion capture (480 Hz) during pitching. Howenstein *et al.*[26] examined the pitching mechanics of 24 youth baseball players throwing fastballs and found that the horizontal ground reaction force impulse generated by the drive and stride legs contributes to the energy transfer between key segments of the lower and upper extremities. They proposed that the propulsion kinetics of the drive leg facilitate the transfer of linear power through the pelvis and trunk, aiding in the throwing motion, while the braking kinetics of the stride leg contribute to the generation of rotational power, which is then transferred between the trunk and arm segments via the shoulder joint. Naito *et al.*[27] measured the pitching movements of ten male collegiate baseball pitchers and identified how the maximum throwing arm endpoint velocity is determined by muscular and nonmuscular interactive torques, considering the dynamic coupling among the trunk, thorax, and both throwing and non-throwing arm segments. DeFroda *et al.*[28] reviewed four studies on 2D video analysis for pitching, comparing 2D videos with 3D motion analysis, and introduced methods for assessing pitching biomechanics using 2D video analysis. Additionally, DeFroda *et al.*[29] developed a 20-item scoring tool (Assessment of Biomechanical Efficiency System, ACES) based on the 2D video analysis of twenty baseball pitchers aged 12–18 years and evaluated the reliability of the tool.

In this study, we explored advanced methodologies for evaluating and preventing injuries specific to throwing sports by examining publicly available videos of professional pitchers recorded with a high-end broadcast camera system equipped with a CMOS image sensor. We utilized 2D motion analysis, pitching mechanics, and inverse dynamics to examine the time variations of joints, the ball, external forces, and elbow varus torque during each phase of pitching. The goal is to identify motion differences among high-intensity professional athletes. The findings aim to provide insights for coaches to enhance technical training in baseball and assist beginners or amateur players in adjusting their movements to prevent sports injuries.

2. Data, Materials, and Methods

There is no way to invite the highest-level MLB pitchers to the lab for biomechanical measurements. Thanks to the advanced broadcast camera systems around the baseball park, videos of each MLB game are available online to the public. Kerschbaumer(30) reported that major broadcast television networks, such as NBC and CBS, are equipped with a mix of Sony HDC-5500 and HDC-3500 cameras that feature CMOS image (motion) sensors, high dynamic range, and high frame rate capabilities. The recorded sports videos are made available to the public on the internet. Motion sensors play a critical role in capturing movement data for kinematic and kinetic analyses. These sensors enable the recording of high-speed motion videos, facilitating the detailed tracking of body segment displacement, velocity, and acceleration. By integrating sensor-based motion capture technology with biomechanical modeling, we assessed movement patterns and the forces and torques acting on the elbows of baseball pitchers.

In this study, we analyzed footage (videos) of seven elite pitchers from publicly available MLB games using the 2D motion analysis software Kinovea. In this analysis, we focused on examining the relationship between ball speed and upper limb movement, stride distance, maximum external rotation, as well as the variations in knee joint angles of the lower limbs from the acceleration phase to the follow-through phase, and whether these variations correlate significantly with ball speed. Additionally, an inverse dynamics approach was conducted to obtain the injury-related maximum external force and maximum elbow varus torque generated by the ball. The research flow chart is shown in Fig. 3.

2.1 Subject selection criteria

We screened seven publicly available videos of elite MLB pitchers for analysis. Seven pitchers with notable achievements and an average fastball speed exceeding 150 km/h were selected. Subject 1 is a relief pitcher, while the remaining six are starting pitchers. The basic information of the selected seven elite pitchers is presented in Table 1. Unfortunately, all of them exhibit different levels of injuries to the arm, shoulder, knee, and so forth.

2.2 Measuring tool: 2D motion analysis software Kinovea

The 2D motion analysis software Kinovea is open-source freeware, making it easy for sports coaches to analyze and study athletes’ movements. Its basic functions include distance measurement, semi-automatic tracking, marking, output analysis, and the comparison of two

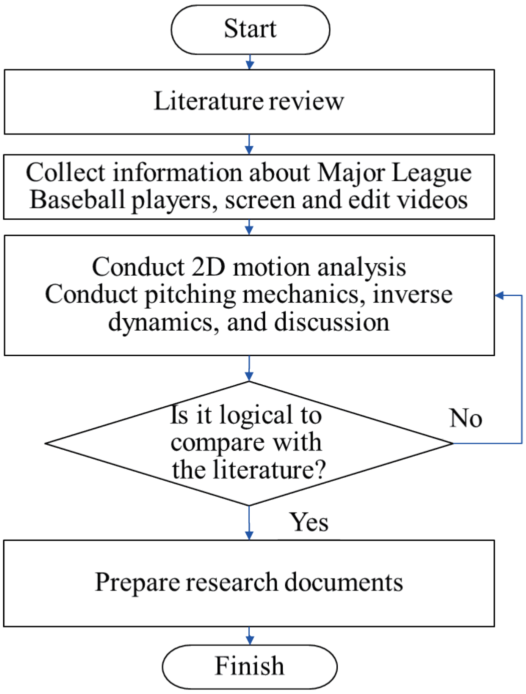

Fig. 3. (Color online) Research flowchart.

Table 1
Basic information of the subjects.

Subject	Height (cm)	Weight (kg)	Age	Fastest ball speed (km/h)	Special achievements	Injury record
1	193	98	29	169.14	MLB All-Star Game	Inflamed rotator cuff, left knee tendinitis, hand injury
2	193	102	29	158	National League Cy Young Award	Elbow, shoulder, back, pelvis, forearm surgery
3	191	102	31	161	American League Cy Young Award	Right shoulder inflammation, bursitis
4	198	102	40	156	American League Cy Young Award	Rotator cuff surgery, back injury
5	193	102	31	158	National League Cy Young Award	Meniscus, elbow surgery, hamstring injury
6	193	104	29	166	National League Strikeout King	Tommy John surgery, thoracic outlet syndrome,
7	180	77	33	159	National League Cy Young Award	Elbow injury

videos. The sampling rate of Kinovea is set at 33 frames per second. Tracking the coordinates of the ball frame by frame is a tedious task, involving setting the working zone, establishing the origin of the coordinate system, identifying the pitcher's height in the video, setting the time unit, tracking the ball coordinates frame by frame, and exporting the 2D coordinate and time values of each point on the trajectory to Excel files. The sampled pitching trajectory and the angle of maximum external rotation (i.e., 83° in this case) obtained from Kinovea are shown in Figs. 4 and 5, respectively.

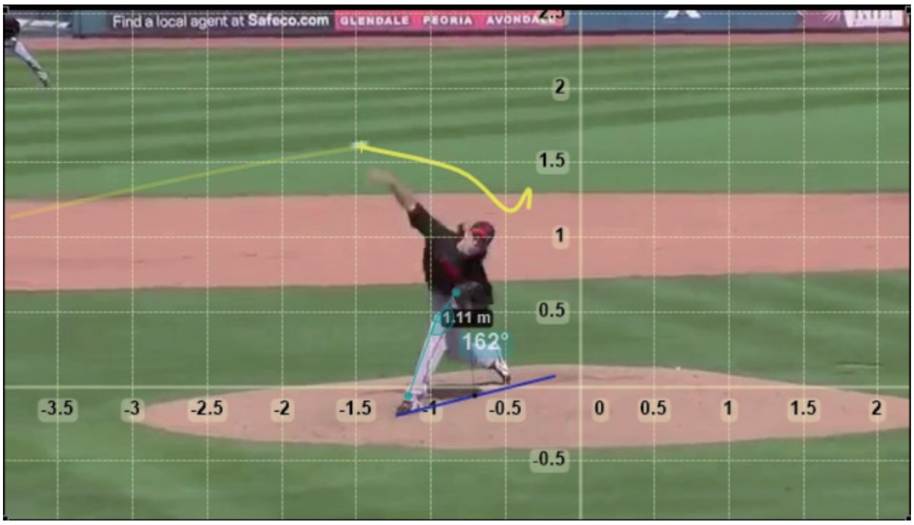

Fig. 4. (Color online) Pitching trajectory measured from Kinovea.

Fig. 5. (Color online) Maximum external rotation angle measured from Kinovea.

These seven selected videos were edited to extract relevant segments for analysis. The research focused on the phase of the pitching motion that significantly affects ball speed - the acceleration phase. Key points in the pitching motion include lead foot touchdown, stride distance, the maximum external rotation of the elbow, and ball release. The objective is to obtain data such as the displacement, velocity, and acceleration of the ball before release, trajectory, the maximum external rotation angle of the elbow, and stride distance from the videos for subsequent analysis, comparison, and synthesis. The injury-related maximum external force and maximum elbow varus torque generated by the ball were also obtained through an inverse dynamics approach.

3. Results

3.1 Trajectories

The throwing motion trajectory of each elite pitcher was obtained. The pitching trajectories of all seven players were combined in one graph, as shown in Fig. 6. In general, the distance the ball moves during the acceleration phase of pitching is within 4 m on the horizontal *x*-axis and 0.8 m on the vertical y-axis. Subject 1 has the shortest distance in both the *x*- and *y*-axes. The trajectory plot of subject 7, captured from the videos in Fig. 6, is the same as the yellow curve shown in Fig. 4. Each pitcher follows a different initial throwing path that gradually converges to a similar pattern. The ball release point of each pitcher is different.

3.2 Time-varying displacement, velocity, and acceleration

It is important for coaches and players to understand the pattern of the pitching process. Pitchers aim for extreme ball speed to increase their chances of being selected for the Major Leagues. The fundamental technique of video analysis is to capture the displacement, velocity, and acceleration of the ball during the pitching period.

The time-varying instantaneous displacement of the ball is calculated from the *x* and *y* coordinates of each pair of successive points in the acceleration phase, as shown in Fig. 7. Essentially, the displacement increases after each data point until the moment of ball release.

The time-varying instantaneous velocity of the ball was calculated by taking the derivative of displacement with respect to time, as depicted in Fig. 8. Each pitcher's ball velocity curve

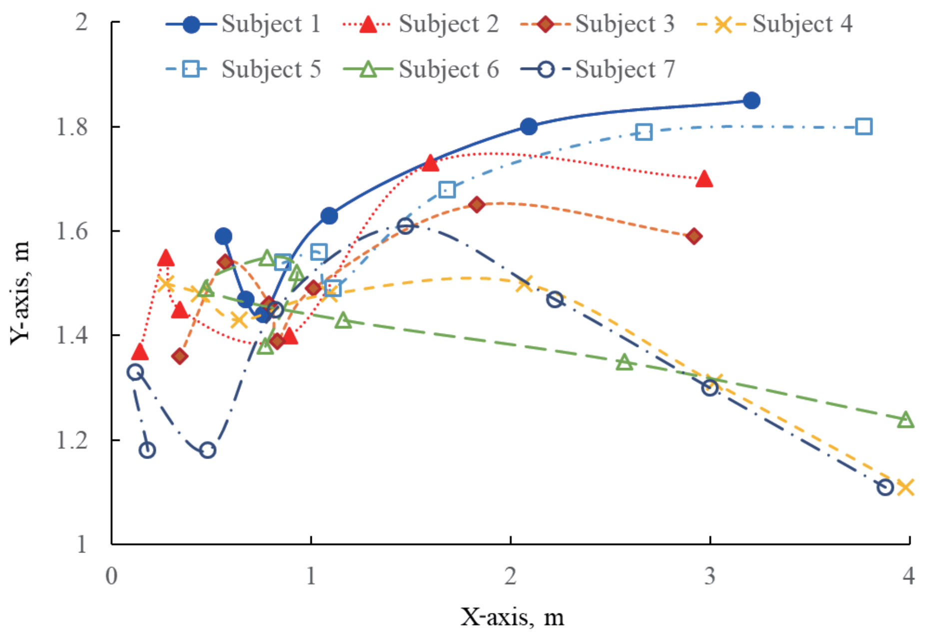

Fig. 6. (Color online) Pitching trajectories of all seven subjects.

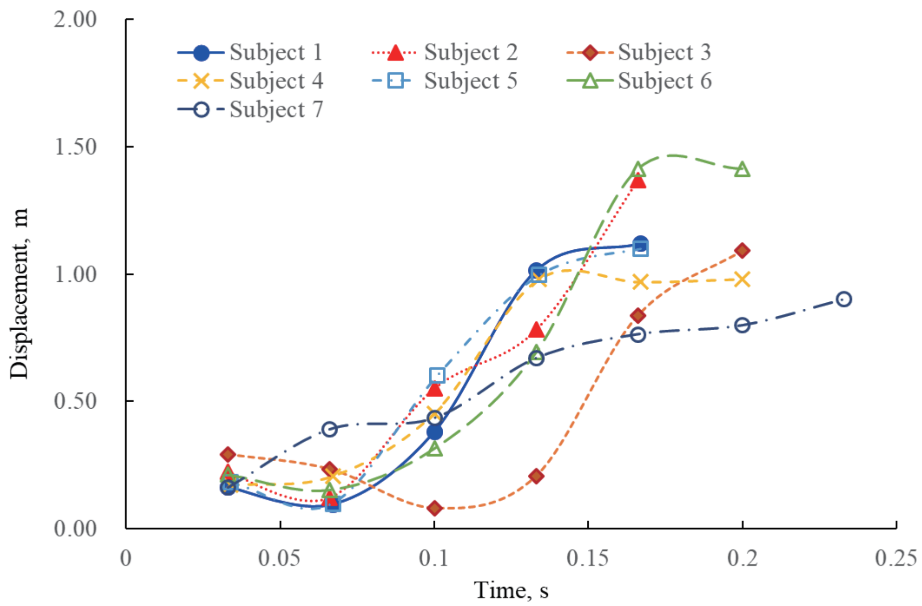

Fig. 7. (Color online) Time-varying displacement plot of different subjects.

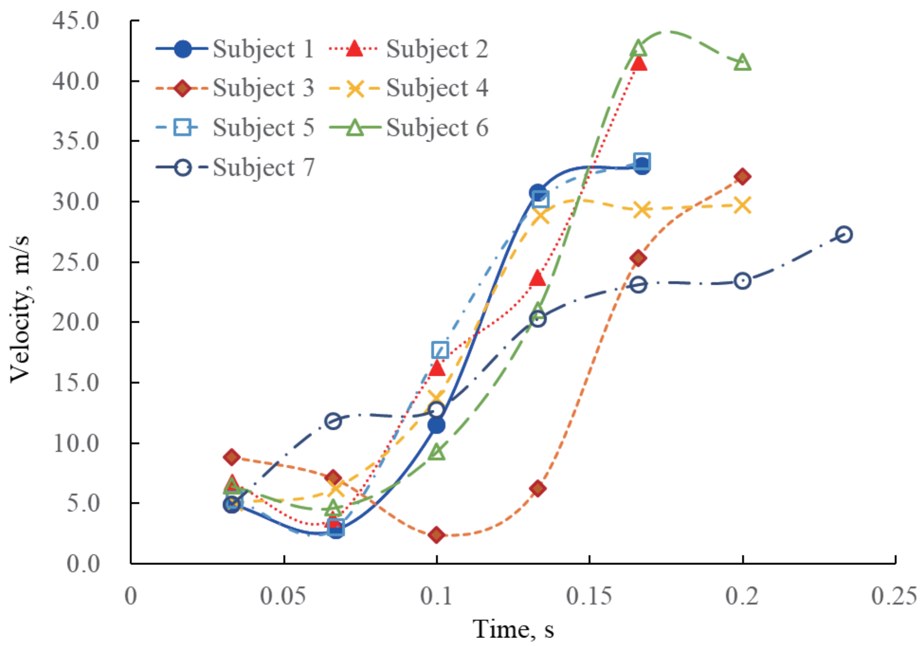

Fig. 8. (Color online) Time-varying velocity plot of different subjects.

differs, but it continuously increases until the ball is released. Subject 6 exhibits the highest displacement and velocity among the players.

Similarly, the time-varying instantaneous acceleration of the ball is calculated by taking the derivative of velocity with respect to time, as shown in Fig. 9. Typically, each subject's data

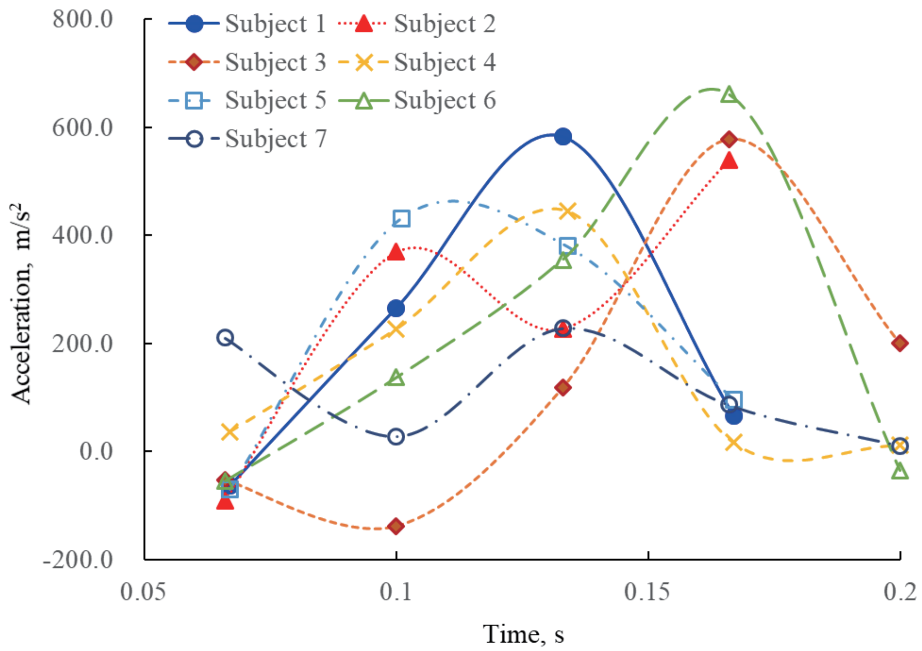

Fig. 9. (Color online) Time-varying acceleration plot of different subjects.

shows that the ball's acceleration increases to a peak at different times, then rapidly decreases to zero, even as the velocity continues to increase just before the ball is released. The muscles in the throwing kinetic chain provide the acceleration force and initiate deceleration before ball release to protect the arm from injury.

3.3 Comparative analysis of basic parameters affecting ball speed

The parameters of interest captured from the videos (excluding MLB records) are listed in Table 2, including height, weight, stride length, ball travel distance, maximum external rotation (max ER), maximum knee joint angle, maximum external force, maximum elbow varus torque, captured maximum speed, and fastest ball speed (MLB record). Table 2 is ordered by the fastest ball speed (MLB record). The column titled 'Captured maximum speed, km/h' contains velocities converted from m/s to km/h for comparison with the fastest ball speed recorded for each elite player in the Major League. The relative errors are computed using Eq. (1).

$$Relative\,errors = \left|\frac{(\mathrm{B})\,Fastest\,ball\,speed\,(MLB\,records) - (\mathrm{A})\,Captured\,\max imum\,speed}{(\mathrm{B})\,Fastest\,ball\,speed\,(MLB\,records)}\right| \quad (1)$$

According to Eq. (1), the relative errors between the two speeds range from 0.05 (for subject 2) to 0.55 (for subject 1), as shown in Table 2. These errors are attributed to camera alignment with the pitcher. These online videos are intended for entertainment rather than scientific

Table 2
Parameters captured from the videos, excluding MLB records.

Subject	Height (m)	Weight (Kg)	Stride length (m)	Ball travel distance (m)	Max ER (deg)	Max. knee joint angle (deg)	Max. external force (nt)	Max. elbow varus torque (Nm)	(A) Captured max. speed (km/h)	(B) Fastest ball speed (MLB record) (km/h)	Relative error, |[(B) − (A)]/(B)|
4	1.98	102	1.72	3.59	68	153	64.66	34.95	106.9	156	0.31
5	1.93	102	1.77	2.98	80	165	62.78	33.08	120.0	158	0.24
2	1.93	102	1.80	3.03	80	154	78.48	41.35	149.5	158	0.05
7	1.80	77	1.75	3.22	87	162	33.13	16.28	98.2	159	0.38
3	1.91	102	1.87	2.45	83	151	84.11	43.86	115.6	161	0.28
6	1.93	104	1.86	3.99	88	137	96.15	50.66	149.7	166	0.10
1	1.93	98	2.10	2.86	92	160	84.65	44.60	76.7	169	0.55

analysis. If the camera's shoot line is not perpendicular to the pitching line and not aimed at the pitcher's center of gravity, perspective distortion can occur. This distortion can make it difficult to accurately measure distances, angles, velocities, and accelerations. However, the captured speed trends closely resemble the MLB records.

3.3.1 Height and weight versus fastest ball speed

The plot of height and weight versus the fastest ball speed is shown in Fig. 10. The graph indicates that there is little correlation between the height and weight and fastest ball speed of the players. Even when subject 7 is excluded from the analysis, the plot remains relatively flat, suggesting little relevance of height and weight to the fastest ball speed. The average height of these seven pitchers is 1.92 ± 0.02 (mean ± standard error of mean) m. The average weight of these six pitchers, excluding subject 7, is 101.67 ± 0.80 kg. Hence, the variations in height and weight are small among the pitchers, which may explain the lack of a positive correlation.

3.3.2 Maximum ER and knee joint angle versus fastest ball speed

The plot of maximum ER and knee joint angle versus the fastest ball speed for different subjects is shown in Fig. 11. The graph indicates a positive correlation between maximum ER and the fastest ball speed of the players: the larger the maximum external rotation angle, the greater the fastest ball speed. However, the maximum knee joint angle does not appear to be relevant to the fastest ball speed in this case.

3.3.3 Stride length and ball travel distance versus fastest ball speed

The plot of stride length and ball travel distance versus the fastest ball speed for different subjects is shown in Fig. 12. The graph indicates a positive correlation between the stride length and fastest ball speed of the players: the larger the stride length, the greater the fastest ball speed. However, the ball travel distance varies considerably with respect to the fastest ball speed, appearing to be irrelevant in this case.

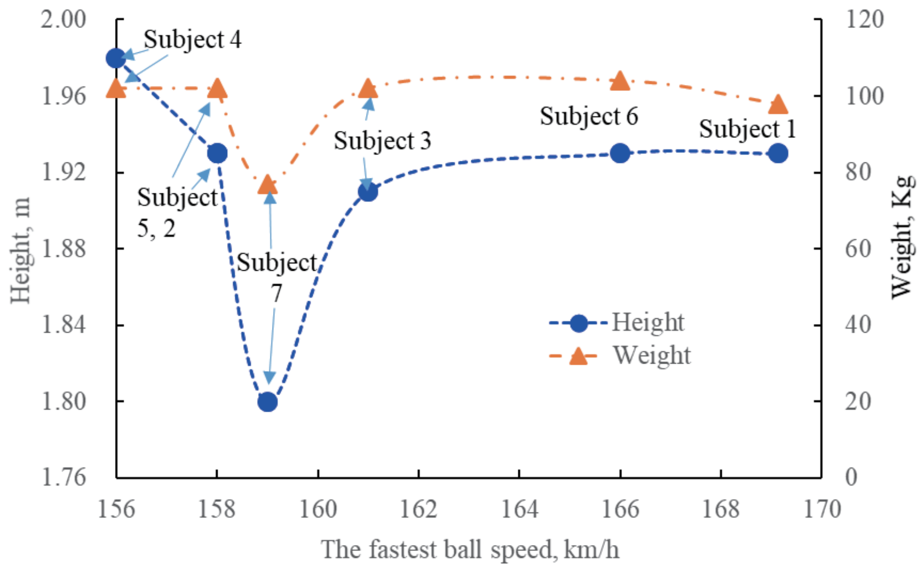

Fig. 10. (Color online) Height and weight versus fastest ball speed for different subjects.

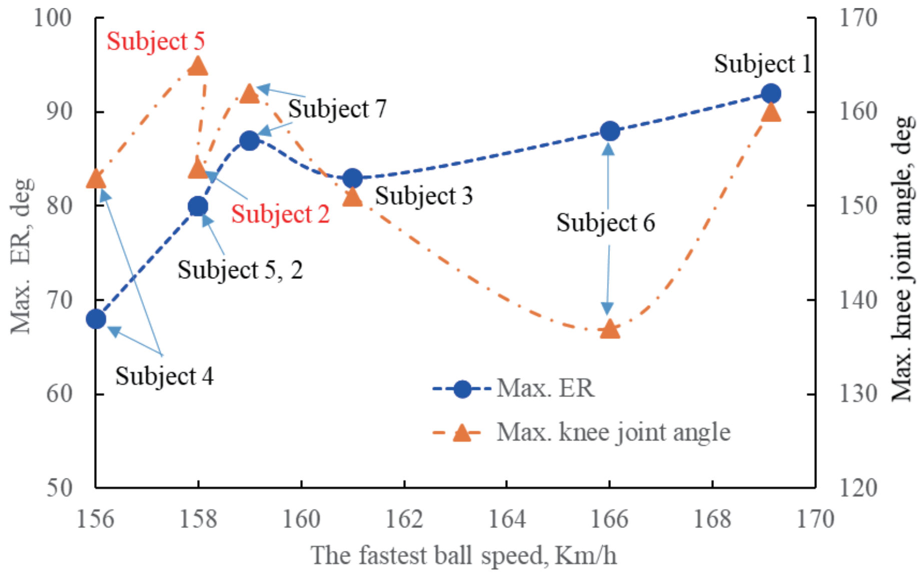

Fig. 11. (Color online) Maximum ER and knee joint angle versus fastest ball speed for different subjects.

3.3.4 Maximum external force and maximum elbow varus torque versus fastest ball speed

The inverse dynamics approach is employed to determine the maximum external force generated by the baseball. The weight of a baseball ranges from 0.142 to 0.149 kg,[31] with 0.145

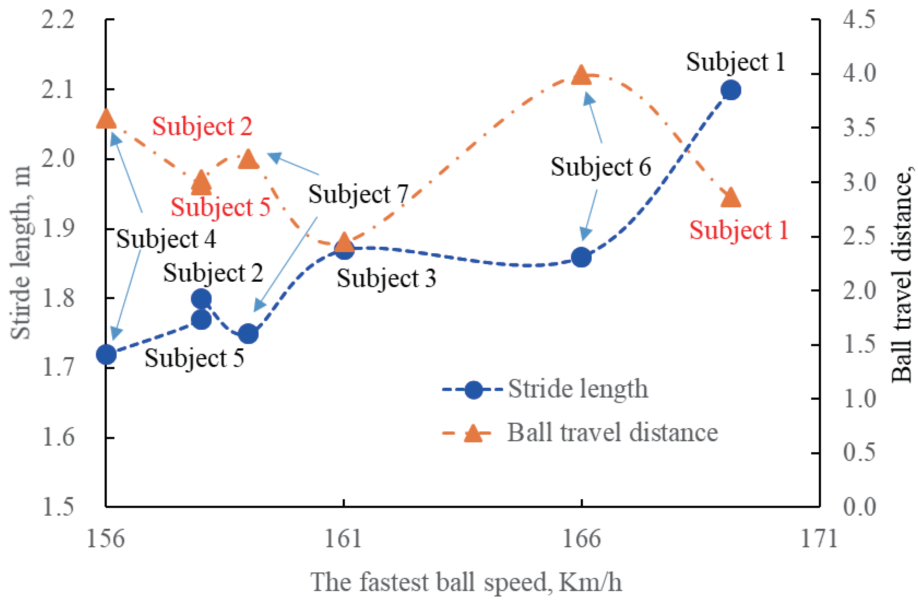

Fig. 12. (Color online) Stride length and ball travel distance versus fastest ball speed for different subjects.

kg being selected for calculations. The maximum external force is calculated by multiplying the maximum acceleration by the ball's weight. To compute the elbow varus torque, the forearm length of each pitcher is needed. Drillis and Contini[32] provided Body Segment Parameters, which are used to calculate forearm length based on the height of each pitcher. Maximum external force and elbow varus torque can be found in Table 2.

The plot of maximum external force and elbow varus torque versus fastest ball speed for different subjects is shown in Fig. 13. The blue and red dotted lines represent the trends of maximum external force and elbow varus torque, respectively, in relation to the fastest ball speed. The graph indicates a positive correlation between both maximum external force and elbow varus torque with the fastest ball speed of the pitchers. As maximum external force and elbow varus torque increase, so does the fastest ball speed.

4. Discussion

4.1 Efficient use of biomechanical parameters by subject 7

Subject 7 is a notable baseball athlete regardless of his smaller body size, standing at 1.8 m, weighing 77 kg, and having a smaller step length of 1.75 m. Despite these physical attributes, he has achieved the status of a starting pitcher in the Major Leagues. Analysis revealed that among seven pitchers (as shown in Table 2), he ranks second in ball travel distance (3.22 m), second in maximum knee joint angle (162 deg), and third in maximum external rotation (87 deg). These factors significantly contribute to his ability to achieve a fastball speed of 159 km/h, which ranks fourth among the seven players. Moreover, upon careful observation of the video, one can notice

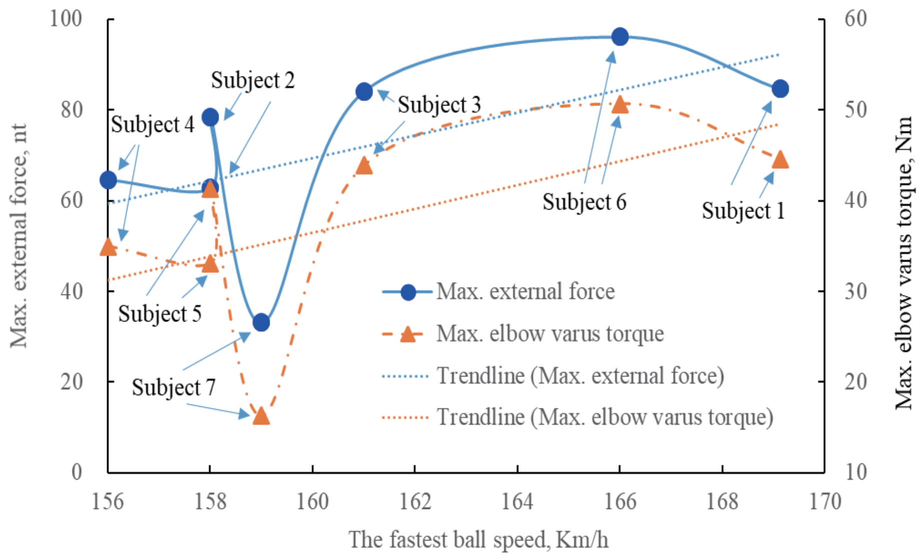

Fig. 13. (Color online) Maximum external force and elbow varus torque versus fastest ball speed for different subjects.

a significant twist angle of the trunk (longitudinal axis of the human body) in Subject 7 compared with the other six pitchers. However, owing to the absence of specific data on the twist angle, this observation lacks solid evidence to support its inclusion in the study.

4.2 Comparison of calculated maximum elbow varus torque with literature results

4.2.1 Comparison with youth baseball pitchers

Saito *et al.*(33) conducted a study involving 164 youth baseball pitchers aged 9 to 12 years old. Each pitcher threw three fastballs while wearing a sensor sleeve that recorded parameters such as medial elbow torque, arm speed, and shoulder rotation. Among pitchers who had sustained injuries less than one year prior, the measured medial elbow torque was 18.6 ± 3.6 Nm. Compared with Saito *et al.*'s results, we reported in this study the average maximum elbow torque as 37.83 ± 4.24 Nm, which is approximately twice Saito *et al.*'s result, as computed from Table 2. Given that professional baseball pitchers are typically twice the age of the youth pitchers recruited by Saito *et al.*, it is expected that MLB players have significantly greater muscle and ligament strengths, developed through years of training than younger athletes. Our results suggest that professional pitchers experience a substantially higher elbow varus torque than youth pitchers, emphasizing the importance of proper biomechanics, conditioning, and recovery strategies to mitigate injury risks.

4.2.2 Comparison with professional pitchers

Manzi *et al.*(34) analyzed 121 professional baseball pitchers using 3D motion-capture technology and found that pitchers with increased lead knee extension at ball release exhibited a lower elbow varus torque, potentially improving accuracy and reducing injury risk. The maximum elbow varus torque values obtained in our study align with the findings from professional-level biomechanical studies. The inverse dynamics approach used here provides comparable estimates of the joint loads experienced during the pitching motion, reinforcing the relationship between ball speed, throwing-arm kinetics, and injury risk.

4.3 Strengths and limitations of this study

In this study, we effectively leveraged motion sensors in broadcast camera systems to capture fast, high-precision motion data of professional pitchers. This enables a noninvasive, real-world analysis of elite athletes without requiring them to be in a laboratory setting. We also applied inverse dynamics approaches to analyze external forces and elbow varus torque, providing quantitative insights into injury risks. By clarifying critical parameters affecting ball speed and injury risk, such as maximum external rotation angle, stride length, maximum external force, and maximum elbow varus torque, our findings provide evidence-based recommendations for performance optimization and injury reduction. This study bridges the gap between sports biomechanics and sensor-based motion tracking, emphasizing the importance of mechanical sensors (force, acceleration, and torque) in sports performance assessment.

However, several limitations were still noted:

1. Absence of bird's-eye view measurements: Top-view videos (filmed from overhead) were not available on the internet, so the twisted angle of the trunk between the wind-up and stride phases could not be measured in this study. A larger twisted angle would increase the ball's travel path and the angular velocity of the trunk during the acceleration phase, resulting in a faster speed at ball release.
2. Potential perspective distortion in video footage: As not all the camera's shoot lines of the online videos were perpendicular to the pitching line or aimed at the pitcher's center of gravity, perspective distortion might occur. This distortion could make it difficult to accurately measure distances, angles, velocities, and accelerations.
3. Lack of 3D motion analysis: We relied on 2D motion analysis using publicly available video footage, which limits the ability to capture depth-related biomechanical parameters. Unlike 3D motion capture systems, which provide more comprehensive kinematic and kinetic data, 2D analysis may introduce errors in angle measurements, joint movement tracking, and force estimations due to perspective distortion.
4. Limited sample size and subject diversity: We only analyzed seven elite MLB pitchers in this research, which provides valuable insights into professional-level biomechanics. However, this sample size is relatively small, and the findings may not be fully generalizable to pitchers at different levels, such as collegiate, amateur, or youth athletes. Expanding the dataset to include pitchers of various skill levels and age groups can improve the applicability of the results.

To solve these problems, more comprehensive motion analysis tools should be implemented for full-body assessments of pitching mechanics in various environments.

5. Conclusions

In this study, we analyzed footage of seven elite pitchers from publicly available MLB games using the 2D motion analysis software Kinovea. The important parameters affecting ball speed include the angle of maximum external rotation, stride length, maximum external force, and maximum elbow varus torque. The conclusions of this study are as follows:

1. The application of CMOS image sensors in broadcast camera systems is essential for capturing motion parameters in the rapid movements of professional pitchers as seen in the seven screened videos.
2. 2D video analysis is an easy way to verify the biomechanical parameters of displacement, velocity, and acceleration of the pitching process. The external force and elbow varus torque produced by the baseball are obtained accordingly.
3. The maximum external rotation and stride length are closely related to the fastest ball speed. The maximum external force and elbow varus torque produced by the baseball are linearly related to the fastest ball speed. They all contribute to upper-extremity-related injury.
4. Other parameters such as height, weight, ball travel distance, knee joint angle, and the twisted angle of the trunk (longitudinal axis of the human body) are also considered to be important for increasing ball speed. However, owing to limited data on the twist angle and an insufficient sample size, the effectiveness of these factors cannot be confirmed.
5. To facilitate the identification of mechanical flaws and aids in the development of targeted interventions to enhance performance and reduce injury risk among professional pitchers, integrating advanced motion-analysis and sensor-based biomechanical feedback systems, such as multi-angle calibrated camera systems, inertial measurement units (IMUs), force plates, and wearable motion sensors, may be our future research directions.

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