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Biomechanics of Elite Athletes: Analyzing Key Kinematic and Kinetic Variables

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Abstract:
With an emphasis on important kinematic and kinetic factors, the biomechanical examination of elite athletes is essential to understanding the complexity of athletic performance. Through examining joint angles, segmental kinematics, and center of mass (COM) kinematics, scientists can better understand the coordination, efficiency of technique, and movement patterns necessary for athletic success. In addition to kinematic analysis, kinetic variables like muscle activity (EMG), joint moments, and ground reaction forces (GRF) can be examined to learn more about propulsion, braking, muscular contributions, and injury risk factors. In addition, measuring biomechanical efficiency, energy expenditure, and power output makes it possible to optimize training regimens specific to each athlete, improving performance and lowering the risk of injury. By incorporating cutting-edge biomechanical assessment techniques, coaches, trainers, and researchers can more easily implement evidence-based interventions that lead to gains in elite athletes' athletic performance and injury prevention tactics.

Keywords:athletes, biomechanics, kinematics, performances

1. Introduction

Understanding the physical performance of top athletes is largely dependent on biomechanics, which offers insightful knowledge into the complex interactions between important kinematic and kinetic variables that characterise their extraordinary ability. Researchers can uncover the mysteries behind the amazing achievements of elite athletes and improve training methods for improved athletic performance by examining the biomechanics of these athletes. Because of their enhanced neuromuscular coordination, biomechanical modifications, and optimized energy transfer systems, elite athletes move with extraordinary efficiency and precision. Key kinematic variables like joint angles, segmental velocities, and body postures during sports tasks can be measured and assessed by researchers using sophisticated motion analysis tools.[1] Furthermore, kinetic variables such as forces, torques, and power outputs can be assessed to obtain important insights into the fundamental processes guiding the performance of elite athletes. The examination of the biomechanical makeup of top athletes can provide important information about how to improve technique, avoid injuries, and boost performance. In order to optimize athletic potential and reduce the likelihood of injuries, coaches and sports scientists can customise training regimens by identifying biomechanical inefficiencies and optimizing movement patterns. In order to better understand the biomechanics of top athletes, this study will examine the important kinematic and kinetic factors that support their remarkable performance. This aims to further sports science and athletic training techniques by combining the results of recent research and investigating useful applications. [2]

2. LITERATURE REVIEWS

Hanley et al., (2023) [3] elucidated the changes in running biomechanics during the 2017 IAAF world championships men's 1500 m final. The objective was to examine important global, spatiotemporal, and kinematic mechanical traits in elite middle-distance competitions. In the 2017 IAAF World Championship 1500m final, eight men was recorded halfway along the home straight on the second, third, and final laps. Three high-definition camcorders' worth of video footage (150 Hz) was digitalized to compute pertinent variables, which was then examined in connection to running position and speed. Finishers in a better position demonstrated longer over striding distances, more knee excursion during stance and higher hip extension during initial contact and late stance. The fastest runners focused on increasing step frequency; therefore, step length did not change with speed. However, the athletes who finished first had longer contact phases and more variations in step cycle speed, which were associated with higher normalised peak horizontal forces. The top athletes also experienced vertical and lower limb stiffness. The longer contact phase and increased compression would enable more sustained force production, which would improve sprinting speed maintenance and acceleration. This would suggest a trade-off between anaerobic power capability and aerobic energetic efficiency. Coaches should be aware that elite 1500-meter runners might prioritize a technique that prioritizes speed over economy, as evidenced by these considerations and the longer over striding distances of the best athletes.

Trasolini et al., (2022) [4] discussed the throwing athlete's biomechanical study and how it affects their comeback to sport." Arthroscopy, Sports involving throwing continue to be a well-liked past time and a common cause of musculoskeletal injuries, especially to the elbow and shoulder. Biomechanical studies of throwing athletes have shown pathomechanic factors that predispose throwers to injury or poor performance. The goal of current research on these variables—often referred to as key performance indicators—is to enhance injury prevention, rehabilitation, and prediction. Important critical performance indicators that have been found in the research to date include shoulder and elbow torque, shoulder rotation, kinetic chain function (as measured by hip-shoulder separation and trunk rotation timing), and lower-extremity mechanics (including stride characteristics).

Currently, marker-based 3-dimensional video motion capture is the gold standard for biomechanical examination of throwing athletes. We may be able to learn more thanks to emerging technologies like wearables, machine learning, and marker-less motion capture. The biomechanics of throwing with a focus on baseball pitching in particular will be covered in this study along with contemporary throwing analytic techniques, their implications for clinical orthopedic practice, and potential directions for future research.

Yang et al., (2022) [5] proposed the comprehension of chasse-step kinematic and kinetic variations in elite table tennis players based on sex. Given the advancements and innovations in table tennis technology, customised training plans might require extra consideration. The purpose of this study was to examine the chasse-step technique in elite table tennis competitors, with an emphasis on the biomechanical variations based on gender. 36 elite table tennis players (18 men and 18 women) competed in topspin forehand and chasse-step. Using marker trajectories and OpenSim (v4.2), angles and moments of the hip, knee, and ankle joints were computed. The ground reaction forces were recorded using the AMTI in-ground force platform and the Vicon motion capture system. During the whole motion period, males exhibited larger flexion angles of the hip and knee, as well as bigger internal rotation angles of the hip during the forward swing phase. In the frontal plane, men's knee joint stiffness was higher than women's knee joint. Compared to males, females displayed higher hip flexion, adduction, and internal rotation moments during the forward swing phase. One theory put up was that the gender differences in physical structures could be the cause of the discrepancy. While female table tennis players should concentrate on hip joint groups to prevent injury, men table tennis players should build their lower limb muscle groups to enhance performance. The study's findings on gender disparities in table tennis players may be useful to coaches and players in creating customised training plans.

Jayathunga Chandana et al., (2022) [6] researched the kinematic study and biomechanical model of the flying phase of hurdle clearance: Finding biomechanical models of the hurdle clearance flight phase that influence hurdle event performance is the aim of this research. This provides crucial advice for coaches and athletes in determining performance standards for a biomechanical hurdle clearance model. The data used in this study are entirely original and were taken from papers that have already been published on the subject of hurdle clearance biomechanics and kinematics in reputable journals. After being evaluated, twenty-six papers were added to the systematic review. Three books were also included in this systematic review to determine the factors to create specific hurdle clearance criteria. Five articles were recognized in the field of the kinematics of horizontal hurdle flight phase, eight articles were recognised in the field of biomechanics. As predicted, the Minimise air time over the hurdle clearing performance is influenced by the appropriate biomechanical model and kinematical variables. Relevant variables are listed together with the relevant supporting data. The phases of takeoff, flying and landing should get special attention. Particularly, an athlete's height and stride length, hurdle height, and hip joint flexibility have all had a big impact on performance.

Walker et al., (2021) [7] evaluated the kinematic elements linked to male world-class sprinters' start performance." The 2018 World Indoor Athletics Championships' top male athletes were the subjects of an investigation into the kinematic variables linked to good sprint performance during the early acceleration phase. Eight sprinters competing in the men's 60-meter final had high-speed video (150 Hz) recorded for them. From the predetermined location to the conclusion of the first ground contact following the block exit, spatiotemporal and joint kinematic variables were computed (GC1). Performance was measured by normalised average horizontal external power (NAHEP), which served as the dependent variable in a number of regression models. GC1 NAHEP was found to have a clear correlation with the 10-, 60-, change in velocity, acceleration, and contact time in the first ground contact. Nearly 90% of the variation in GC1 NAHEP was described by the trunk angle at take-off and the thigh separation angle at take-off, according to stepwise multiple linear regression of joint kinematic variables in the initial ground contact (R2 = 0.89). This will serve as a useful visual aid for technical coaching teaching. The athletes' projection at takeoff, with a forward-leaning trunk and substantial thigh separation, is indicative of excellent initial acceleration performance. This was the first study of its sort to use a world-class sample in a representative setting with such a research strategy. Subsequent research endeavours that integrate comprehensive kinematic and kinetic data collection and examination within this context will enhance the understanding of the outcomes of this inquiry.

Table: 1 Comparative table summarizing the findings of the mentioned studies.

Author & Year	Title	Findings
Hanley et al., 2023	Changes in running biomechanics during the 2017 IAAF World Championships men's 1500 m final	Finishers who were better positioned showed more hip extension during early contact and late stance. - Finishers in better positions showed more knee excursion during stance. - Because runners relied on increasing step frequency, step length stayed constant as speeds increased. - The athletes that finished first showed longer contact phases and more variations in their step cycle speed, which were associated with higher normalised peak horizontal forces. The top athletes possessed both vertical and lower leg stiffness, which improved their ability to accelerate and maintain sprinting pace over longer distances. Elite 1500-meter runners could use a method that emphasises speed above economy.
Trasolini et al. (2022)	Biomechanical analysis of the throwing athlete and its impact on return to sport	Identified kinetic chain function, lower-extremity mechanics, shoulder and elbow torque, and shoulder rotation as critical performance indicators in throwing athletes. Emphasised that the gold standard for biomechanical analysis is marker-based 3-dimensional video motion capture, with new technologies potentially providing improvements. Future directions for study and consequences for clinical orthopedic practice were discussed.

Yang et al. (2022)	Understanding sex-based kinematic and kinetic differences of chasse-step in elite table tennis athletes	Observed notable sex-based variations in the angles and moments of the hip and knee joints during the chasse-step in professional table tennis players. While females displayed more hip flexion, adduction, and internal rotation moments, males displayed greater hip and knee flexion angles. To increase performance and reduce injuries, suggestions for sex-based customized training regimens were given.
Ayathunga & Chandana (2022)	Biomechanical model and kinematic analysis of hurdle clearance flight phase: a review	Examined the kinematic factors and biomechanical theories influencing hurdle clearing performance. identified certain parameters that have a significant impact on performance during the flight phase of hurdle events, including athlete height, stride length, hurdle height, and hip joint flexibility. based on biomechanical data, offered coaches and players tips on how to maximise hurdle clearing performance.
Walker et al. (2021)	Kinematic factors associated with start performance in World- class male sprinters	Examined the kinematic elements linked to male sprinters' successful start performances at the 2018 World Indoor Athletics Championships. It was discovered that the take-off thigh separation angle and trunk angle were the most important indicators of the initial acceleration performance, accounting for about 90% of the variation in performance. Emphasised the need of receiving technical coaching training based on these kinematic considerations.

3. RESEARCH METHODOLOGY

3.1. Understanding the kinematic variables

3.1.1. Study Design:

The study employed a test-retest methodology to assess the inter-session reliability of kinematic variables and short sprint performance. A minimum 48-hour gap between sessions was maintained, during which participants refrained from moderate-to-intense exercise. Cross-sectional design and Pearson correlation analyses were used to examine the relationships between third step sprint kinematics and 5m sprint times.

3.1.2. Participants:

Fifteen physically active volunteers from various sports communities participated, aged between 17 to 27 years. Participants were engaged in running-intensive sports and had at least one year of resistance training experience without recent injuries. Ethical approval was obtained from the institutes' ethics committee and participants provided informed consent.

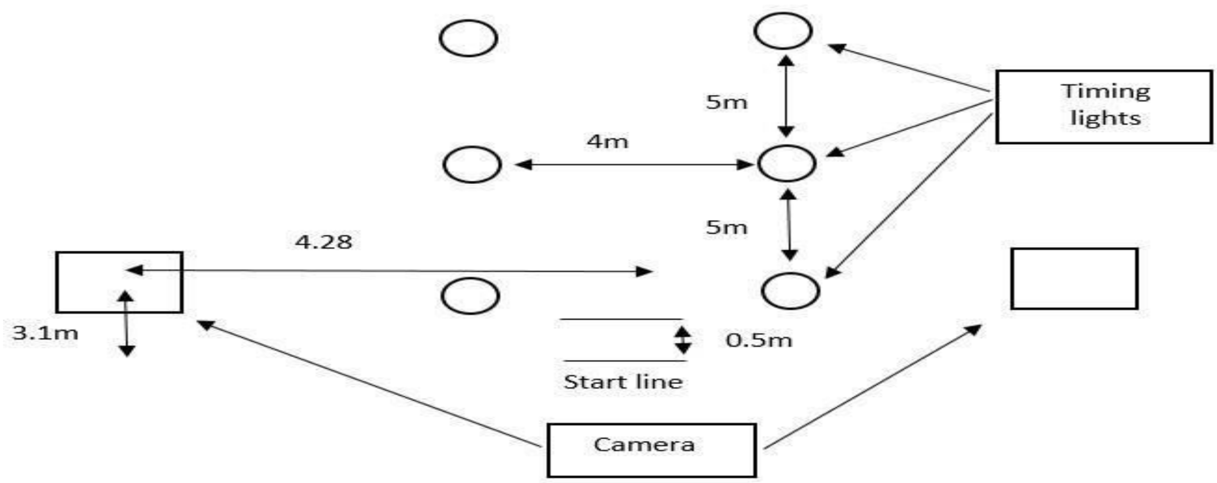
3.1.3. Experimental Procedures:

Each participant underwent two testing sessions—familiarization and data collection. Testing sessions included a self-selected warm-up followed by sprint familiarization and maximal sprint trials. Participants maintained their preferred foot position on the starting line and commenced sprints upon a verbal cue. Testing procedures were repeated in a second session after a minimum 48-hour interval.

3.1.4. Data Collection:

Sprint trials were conducted on rubberized tile flooring using a SWIFT timing light system for performance measurement. High-speed cameras captured kinematic data during the first three sprint steps. Joint markers were plac ed on participants' bodies for precise motion tracking.

Figure 1: Diagram of the equipment setup for testing.



1. Data Analysis:

Silicon-coach pro 7 software was used to analyze kinematic variables across the first three sprint steps. Variables included step length, step rate, stance time, flight time, knee angle at touchdown, and knee angle at take-off. Statistical analyses included coefficient of variation (CV%), intra-class correlation coefficients (ICC), and Pearson correlations.

1.1.Statistical Analysis:

Reliability of performance objectives and kinematic variables was assessed using change in mean ± 90% confidence levels. Outliers were removed, and data was log-transformed to improve interpretability. Descriptors were used to categorize effect magnitudes. Pearson correlations were conducted to determine proportional influence between 5m sprint durations and kinematic variables. SPSS software was utilized for statistical analyses.

2. Understanding the Kinetic Variables by Biomechanics of Throwing ball

5.1 Phases of Throwing

To maximise performance and lower the risk of damage, throwing a ball is a complex movement that involves coordination of several movements in a particular order. Wind-up, stride, arm cocking, arm acceleration, arm deceleration, and follow through are the throwing phases (Fig. 2). Energy is created or transferred from the body to the arm and baseball during each phase.

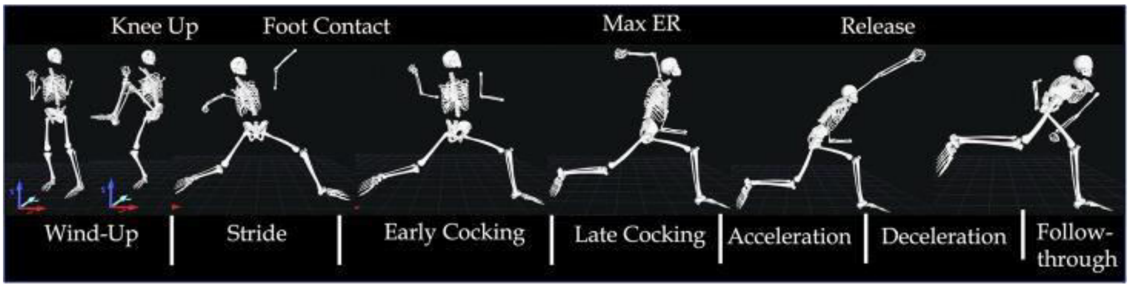


Fig 2. The stages of pitching are illustrated by skeleton diagrams made during the examination of throw videos. [8]

The wind-up phase of the throw starts when the drive leg receives the weight and potential energy is stored as the driving knee bends and the truncal rotation occurs. A hip hinging pattern is displayed by the drive leg in order to trigger the posterior chain. To move the centre of mass over the driving leg, the stride leg, also known as the lead leg, was raised. When the centre of mass starts to move towards the stride leg and the knee lift achieves its maximum, this phase comes to a close.

All movement from the maximum lead knee lift to foot striking is included in the stride phase. The athlete pushes into the ground early in this phase to create a ground response force that will enable them to progress linearly towards their target while maintaining their hip hinge with the drive leg (Fig 3). Stride length has been found to be correlated with elbow varus torque (EVT) and velocity. however, an elbow torque increase may be mitigated by a stride length larger than 80% of body height. Another crucial factor in stride placement is foot placement; the foot should fall parallel to the drive leg and slightly internal. Hip-shoulder separation is a common result of the pelvis rotating separately from the torso as the lead leg approaches the ground. To reduce the risk of injury, the throwing arm should have >90° elbow flexion, >35° shoulder external rotation, and about 90° shoulder abduction by the end of the stride phase.

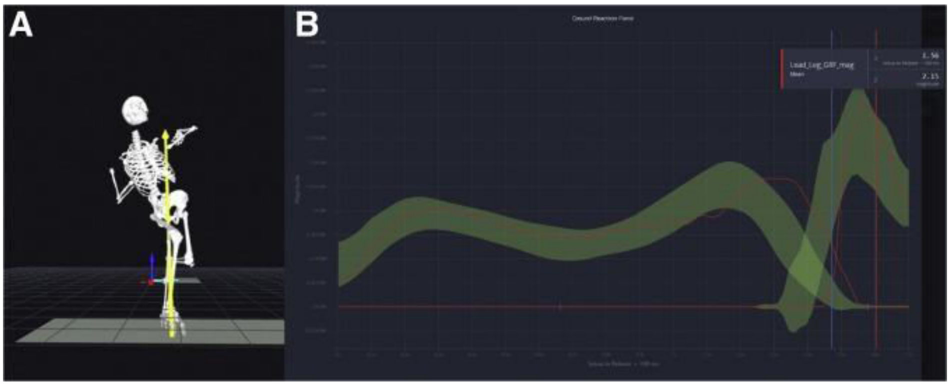


Fig 3. An illustration of measuring ground reaction force in the context of throwing analysis. (A) Skeletal model created using data from three-dimensional markers. The ground reaction force that was obtained by measuring it using force plates inserted into the pitching mound is represented by the yellow vector. (B) An example ground response force graph for the plant leg and lead leg. The mean for collegiate pitchers is shown by the green area.[9]

At foot strike, the arm cocking phase starts, and it finishes at maximum shoulder external rotation (MER). Lead knee flexion should be at its maximum at foot strike and should decrease prior to ball release since the lead leg provides a stable basis for rotation during the rest of the throw. The pelvis should cease spinning quickly after the foot strikes, enabling energy to be transferred to the torso. The hip-shoulder gap that was previously formed will close with upper body rotation, enabling the throwing arm to move even further outside. The shoulder should ideally attain 170° to 180° of MER while keeping the elbow flexion at >90° and shoulder abduction at 90°.9. External rotational restrictions can raise shoulder joint stress and decrease ball velocity.

The arm starts to accelerate in the direction of the throwing target once MER is reached. This phase, which is the interval between MER and ball release, is aptly called the arm-acceleration phase. To generate and transfer as much energy as possible to the arm, the torso tilts forward and rotates continuously until it stops right before the ball is released, allowing the arm to advance towards the target. In order to better stop the pelvis and transfer energy from the lower extremities to the torso and arm, the lead knee is extending during this motion. At the moment of ball release, the elbow extends and the shoulder changes from external to internal rotation. This transfers energy to the hand and baseball. Peak angular velocities for professional pitchers are approximately 6,200 deg/s for shoulder internal rotation and 4,600 deg/s for elbow extension, respectively, during this period, which places the greatest demands on stress and torque on the shoulder and elbow.

The arm deceleration phase lasts until the shoulder's maximal internal rotation after the ball is released. The athlete's arm needs to slow down in a safe, controlled way after reaching this extraordinarily high angular velocity and releasing the ball. The forearm continues to pronate while the chest rotates and tilts forward once again to make room for the arm following ball release. To slow down the arm and lessen joint loading, the muscles in the upper back, chest, shoulder, and arm are highly stressed.

Any movement that occurs after the shoulder achieves its greatest internal rotation until the arm stops moving is referred to as the follow-through phase. Each athlete's version of this phase might vary greatly based on their arm slot, lower body mechanics, and other variables.

5.2 Kinetic Chain

Throwing athletes produce velocity by transferring lower-extremity and core energy synchronistically to the upper-extremities torque, rotation, and angular velocity. The body is loaded like a torsion spring by potential energy that is accumulated during wind-up through weight transfer and truncal rotation. The ball is accelerated in the intended direction by this energy once it has been transmitted to the elbow and shoulder and transformed into kinetic energy and centripetal force. High-level performance and injury prevention depend on the efficient summation and transfer of lower-extremity potential energy and core energy to upper- extremity kinetic energy. The term "kinetic chain" refers to the process that makes that energy transfer possible.

Three elements make up a functional kinetic chain: effective motor patterns, successive force generation, and optimised anatomy. The term "optimised anatomy" describes the power, strength, and flexibility of the body's numerous separate functional segments, or "kinetic links." The feet, lower extremities, hip and pelvis, trunk, scapulothoracic articulation, shoulder and elbow, and distal extremity are important kinetic linkages for throwing. The several parts of the kinetic chain sequentially produce forces during a throw, which are coordinated to accelerate the ball in the intended direction. Minimal energy waste occurs during the transfer between independent parts of the kinetic chain when efficient task-specific motor patterns are used.

Anatomical disruption (loss of shoulder range of motion, lack of hip internal rotation, etc.), improper force distribution between segments (depending too much on arm strength without activating the lower extremities), or ineffective motor patterns (scapular dyskinesis) can all lead to dysfunction of the kinetic chain. According to reports, between 51% and 55% of the kinetic energy transferred to the hand during a throw is accounted for by the legs and trunk. The upper extremity attempts to "catch up" when the kinetic chain is malfunctioning, increasing the stresses on the elbow and shoulder and increasing the risk of injury for athletes.

For strength, range of motion, coordination, and internal derangements, each link in the kinetic chain is assessed independently. It is possible to customise post-injury rehabilitation or preventative training to target weak points in the kinetic chain and enhance segment synchronisation. Kinetic linkages are analysed prior to the throwing task in current throwing analysis. Next, we analyse the kinetic chain's efficiency using video motion capture. A crucial sign of this kinetic chain function is hip-shoulder separation (Fig. 4), which shows how the lower extremities are loaded into a torsion spring through the core. It has been shown that trunk rotation velocity, which in turn corresponds with pitch velocity, is correlated with hip-shoulder separation during front foot contact.

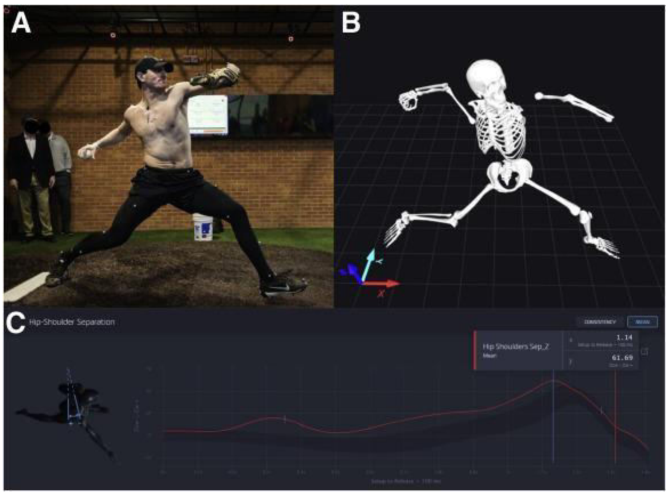


Fig 4. An illustration of a biomechanical throwing study in three dimensions (3D). (A) A pitcher who throws right-handed and has on a 41 retroreflective marker set. (B) Skeletal model created using data from 3D markers. (C) A hip-shoulder separation graph, which is a kinematic metric computed in a three-dimensional biomechanical analysis. It represents the rotational difference between the pelvis and the trunk.[10]

5.3 Shoulder and Elbow Biomechanics

During the stride phase of throwing, the upper extremity becomes active, causing the humerus to abduct into a semicocked position and initially rotate externally. The scapula has six degrees of flexibility, allowing it to extend, tilt anteriorly, and rotate laterally. As the stride comes to a conclusion, the trunk and shoulder translate towards the target, but the elbow and hand lag behind, causing the shoulder to rotate outward extremely. To allow for this movement within the subacromial area, the scapular position adjusts. The scapula is in its maximum retraction, lateral rotation, and posterior tilt position at maximal external rotation. The hand stays on top of the ball while the elbow flexes. In concavity compression, the rotator cuff contracts to keep the glenohumeral joint stable. Right before MER and the maximum elbow varus torque is attained, there is a "critical instant."

A significant amount of potential energy is converted to kinetic energy when the throw moves from late cocking to early acceleration, placing a lot of strain on the elbow and glenohumeral joints. The labrum, rotator cuff, and shoulder capsule must work together to resist shear stresses applied to the anterior and superior aspects of the joint. The biceps, triceps, and flexor pronator mass partially buffer the ulnar collateral ligament from a supraphysiologic valgus stress at the elbow. At this point, the elbow flexion angle controls the axial torque acting on the humerus and glenohumeral joint by determining the perpendicular distance between the ball and the humerus' long axis. To lessen the upper extremity kinetic link's moment of inertia and enable higher angular velocity with less torque, elbow extension starts just before to humeral internal rotation.

As the ball accelerates towards the target, humeral internal rotation and elbow extension are required to complete the throw. The arm goes through a second "critical instant" after the ball is released, which is when the maximum glenohumeral distraction force happens. The infraspinatus, teres minor and major, latissimus dorsi, and posterior deltoid must all be forcefully contracted in order to securely decelerate, compress, and stabilise the shoulder. The elbow flexors must contract eccentrically in order to slow down elbow extension. The trapezius, rhomboids, and serratus anterior work together to cause the scapula to slow down and rotate back into its resting position. When the arm achieves its terminal position of internal rotation and adduction, the follow through finally releases the residual kinetic energy of the throw through the stride leg.

The goal of contemporary throwing analysis is to use a collection of recorded throws to capture a broad range of the biomechanical characteristics previously addressed. Throughout the throwing process, these variables—known as key performance indicators, or KPIs—are compared to population norms at a certain level of competitiveness.

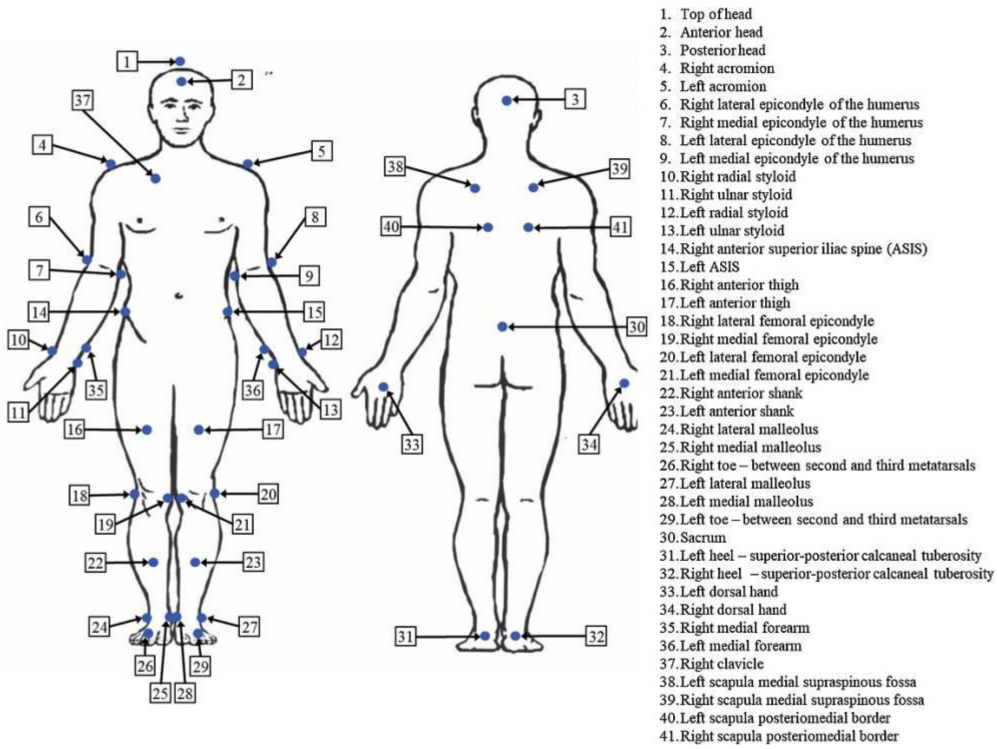


Fig 5. Marker locations for video motion capture throwing analysis.[11]

To put it briefly, players come in for a functional movement evaluation and physical assessment first. The warm-up that comes next is dependent on the player's preference. After applying motion-capture markers, the video motion capture apparatus is adjusted. Lastly, once each player throws a number of pitches, they will be examined for key performance indicators (KPIs), as listed in Table 2. Following this examination, a follow-up meeting is planned to go over the findings and inform the athlete about biomechanical variables that could put them at risk for injury or subpar performance.

Table 2. Key Performance Indicators (KPIs) Measured

Ball Speed	Shoulder Abduction/horizontal Abduction at Foot Strike
Stride length	Shoulder abduction at release
Back leg GRF max	Maximum shoulder external rotation (MER)
Lead leg GRF max	Elbow angle at MER
Pelvis rotation at MER	Elbow angle at release
Hip-shoulder separation at foot strike	Elbow angle at foot strike
Trunk lateral tilt at foot strike	Max elbow varus torque
Trunk forward flexion at foot strike	Thorax angular velocity max
Knee flexion angle at release	Humerus angular velocity max
Trunk forward flexion at release	Elbow extension velocity max
Trunk lateral tilt at release	Pelvis angular velocity max
Trunk rotation at release	Lead knee angular velocity max
Time between max pelvis rotation velocity and max trunk rotation velocity	

After reviewing the connection between throwing mechanics and injury, Chalmers it is found that fatigue, shoulder external rotation torque, elbow varus torque, altered knee flexion at ball release, and early trunk rotation (i.e., loss of hip–shoulder separation) were the most important factors.

A lot of research has been done on elbow varus torque. The arm slot at ball release, MER, and pitch velocity are all connected to elbow varus torque. There have been reports of correlations between elevated risk of elbow injuries and elbow varus torque. In a research with twenty-three professional pitchers followed up for three years following a pitching analysis, elbow injury rates were higher in those with higher torque values in the shoulders and elbows. During throwing analysis, additional pathogenic KPIs that are measured include early trunk rotation and lack of hip-shoulder separation. As mentioned, these parameters are assessed in order to determine whether the thrower has kinetic chain dysfunction. It has been demonstrated that improper trunk rotation sequences increase shoulder stresses by 9.2% body weight. Although the majority of throwing evaluations take place during a brief pitching session with few pitches, this may not be able to detect fatigue-related pathomechanics. the pitch count grew in a study involving pitchers, kinetic chain mechanics deteriorated. More specifically, upper- extremity factors did not change, although hip-shoulder separation did. Transferring energy through the core muscles requires the separation of the hips and shoulders. In order to obtain the same energy at ball release with less efficient core muscle energy transfer, the thrower's elbow and shoulder are put under more strain. Pitchers in this study lost velocity as a result, and as the number of pitches grew, so did the number of claims of arm pain. An additional study that involved pitchers in a simulated game especially looked at the effect of fatigue on elbow varus torque. Medial elbow torque started to rise by 0.84 Nm each inning after the third inning.

Because external rotation motion restriction has been linked to an increased risk of injury, static shoulder range of motion is particularly important. Throwing athletes with preseason external rotation limitation (defined as throwing arm <5° greater than non-throwing arm) had an odds ratio of 1.90 for an elevated risk of injury in a comprehensive review and meta-analysis of 15 studies.39 It should be mentioned that since all throwing athletes were included in this study, conclusions might not apply to baseball players exclusively. Internal rotation and total range of motion were found to be significant predictors of injury, while external rotation was not, in a more focused meta-analysis of three studies examining range of motion in baseball throwers.

3. RESULTS

The study employed a test-retest methodology to assess the inter-session reliability of kinematic variables and short sprint performance, with a minimum 48-hour gap between sessions to ensure participants refrained from moderate-to-intense exercise. A cross-sectional design and Pearson correlation analyses were utilized to examine the relationships between third step sprint kinematics and 5m sprint times.

Table 3 presents group averages and standard deviations assessing test-retest reliability between the first and second sessions. Despite moderate to high levels of session similarity, neither of the performance variables (5- and 10-meter sprint times) met the requirements for high or adequate reliability.

The kinematic measures demonstrated substantial reliability and associations with sprint times. Second and third step step frequency, second and third step stance time, third step knee angle on touchdown, and second step trunk angle at take-off exhibited "very large" levels of relatedness between sessions. First step step frequency, second step step length, first step stance duration, first and second step knee angles at touchdown, first step knee angle at touchdown, and first and third step trunk angle at take-off displayed high levels of dependability.

However, flight time failed to meet the minimum reliability standards of "adequate" in any of the first three steps. Correlations between the third step kinematic characteristics and 5m sprint performance indicated that step frequency and flight duration had the highest associations, while step length and stance time showed relatively smaller links.

While sprint performance reliability varied, kinematic variables demonstrated substantial reliability and associations with sprint times, highlighting their importance in understanding sprint mechanics and performance optimization. Further research is warranted to explore additional factors impacting sprint performance comprehensively.

Table 3: Coefficient of variance and retest correlation for the kinematic variables and performance measures from Day 1 and Day 2

Variable	Step	Day 1	Day 2	Change in Mean (Units)	CV%	ICC	Reliability Factor
5m time	-	1.14	1.08	-0.06	4.9	0.35	Nil
10m time	-	1.87	1.92	0.05	3.7	0.59	Nil
Step	1	4.53	4.56	0.03	3.3	0.80	High

frequency (Hz)	2	4.76	4.70	-0.06	3.1	0.67	Adequate
	3	4.70	4.76	0.06	3.5	0.73	Adequate
Step length (m)	1	0.99	0.97	-0.02	8.5	0.60	Nil
	2	1.11	1.14	0.03	4.8	0.77	High
	3	1.25	1.23	-0.02	6.7	0.41	Nil
Stance time (s)	1	0.179	0.187	0.008	5.9	0.89	High
	2	0.162	0.170	0.008	7.3	0.70	Adequate
	3	0.152	0.152	0.000	8.1	0.69	Adequate
	1	0.041	0.039	-0.002	33.5	0.65	Nil
Flight time (s)	2	0.048	0.043	-0.005	18.9	0.38	Nil
	3	0.062	0.057	-0.005	19.2	0.41	Nil
Knee angle at touchdown (°)	1	115	117	2.0	3.6	0.80	High
	2	122	125	3.0	2.9	0.75	High
	3	124	127	3.0	3.0	0.72	High
Knee angle at take-off (°)	1	152	154	2.0	1.9	0.82	High
	2	156	154	-2.0	3.3	0.55	Nil
	3	156	159	3.0	2.1	0.66	Adequate
Trunk angle at take-off (°)	1	41	42	1.0	4.7	0.87	High
	2	46	47	1.0	4.1	0.68	Adequate
	3	49	50	1.0	2.7	0.94	High

Table 4: Correlations between the 5 m sprint performance and third step kinematic characteristics

Kinematic Characteristic	Correlation coefficient 'r'	90% Confidence Interval	Qualitative Inference
Step Frequency (Hz)	-0.378	-0.79 to 0.25	Small
Step Length (m)	-0.245	-0.69 to 0.36	Very Small
Stance Time (s)	-0.075	-0.64 to 0.52	Very Small
Flight Time (s)	0.415	-0.23 to 0.80	Small

The kinetic variables involved in throwing a ball, encompassing phases like wind-up, stride, arm cocking, acceleration, deceleration, and follow-through, are crucial for maximizing performance and minimizing injury risk. A functional kinetic chain, facilitated by effective motor patterns, successive force generation, and optimized anatomy, ensures the synchronized transfer of energy from lower extremities and core to upper extremities, accelerating the ball efficiently. Dysfunction in this chain, caused by anatomical disruptions, improper force distribution, or ineffective motor patterns, heightens injury susceptibility. Throwing analysis, focusing on key performance indicators (KPIs) such as ball speed, shoulder abduction, stride length, and trunk rotation, aids in evaluating performance and

identifying injury risks. Moreover, considerations like fatigue, shoulder and elbow biomechanics, and range of motion significantly impact injury risk and performance outcomes. Comprehensive understanding and assessment of these biomechanical aspects are imperative for optimizing throwing performance and safeguarding athletes from injuries.
The key benefits of conducting research on "Biomechanics of Elite Athletes: Analyzing Key Kinematic and Kinetic Variables" include:
Performance Optimization: By analyzing key kinematic and kinetic variables, researchers can identify biomechanical factors that contribute to elite athletic performance. Understanding how these variables influence movement patterns allows coaches and athletes to optimize training regimens and techniques for improved performance outcomes.

- Injury Prevention: Biomechanical analyses can help identify movement patterns and biomechanical imbalances that may predispose elite athletes to injuries. By addressing these issues through targeted interventions and corrective exercises, athletes can reduce the risk of injury and maintain peak physical condition.

- Talent Identification and Development: Studying key kinematic and kinetic variables in elite athletes can aid in talent identification and development programs. Coaches and talent scouts can use biomechanical assessments to identify athletes with potential and tailor training programs to enhance their strengths and address weaknesses.

- Personalized Training Programs: Biomechanical analyses provide valuable insights into individual athlete characteristics and movement patterns. This allows coaches to develop personalized training programs that are tailored to the specific needs and biomechanical profiles of each athlete, maximizing their potential for success.

- Enhanced Coaching Strategies: Coaches can use biomechanical data to inform coaching strategies and techniques. By understanding how key kinematic and kinetic variables influence performance, coaches can provide more targeted feedback and instruction to help athletes refine their skills and optimize their performance.

- Scientific Understanding of Athletic Performance: Research on key kinematic and kinetic variables contributes to the scientific understanding of athletic performance. By advancing our knowledge of biomechanics in elite sports, researchers can uncover new insights into the factors that drive human performance and push the boundaries of athletic achievement.

- Competitive Advantage: Athletes and teams that leverage biomechanical insights to optimize training and performance strategies gain a competitive advantage over their rivals. By fine-tuning biomechanical variables, athletes can enhance their speed, power, and efficiency, giving them an edge in competitive sports environments.

- Injury Rehabilitation: Biomechanical analyses can also be used in the rehabilitation of injured athletes. By identifying movement compensations and biomechanical deficits, healthcare professionals can develop targeted rehabilitation programs to restore optimal movement patterns and facilitate a safe return to sport.

Overall, the study "Biomechanics of Elite Athletes: Analysing Key Kinematic and Kinetic Variables" has a lot to offer in terms of improving elite sports performance, athlete development, and sports science.

4. Discussion

The study "Biomechanics of Elite Athletes: Analyzing Key Kinematic and Kinetic Variables" employed a rigorous test-retest methodology, incorporating a 48-hour gap between sessions, to evaluate the inter-session reliability of kinematic variables and short sprint performance among elite athletes. Utilizing a cross-sectional design and Pearson correlation analyses, the research aimed to elucidate the relationships between third step sprint kinematics and 5m sprint times. However, despite the meticulous approach, several limitations and opportunities for future investigation were identified. Analysis of the data presented in Table 3 revealed intriguing insights. While kinematic measures, particularly second and third step variables such as step frequency and stance time, demonstrated substantial reliability, the reliability of sprint performance measures, as indicated by 5- and 10-meter sprint times, did not meet high or adequate standards. This discrepancy suggests potential issues with measurement consistency in sprint performance assessment, prompting further scrutiny into the methodology employed or instrumentation used for data collection. Furthermore, the failure of flight time to meet reliability standards across initial steps, as evidenced by the data provided, raises questions about the accuracy and consistency of this critical kinematic variable. These findings underscore the need for methodological refinement or alternative approaches to ensure the accurate capture of key variables. Additionally, while correlation analyses provided valuable insights into the relationship between kinematic characteristics and sprint performance, the study's scope may not have comprehensively explored all factors influencing sprint performance. The correlations presented in Table 4 offer valuable insights, with step frequency and flight duration demonstrating the highest associations with sprint performance. However, future research should consider investigating additional variables or potential confounders that may impact sprint performance outcomes. Moreover, the study's reliance on Pearson correlation analyses may overlook potential nonlinear relationships or interactions between variables, suggesting the need for alternative statistical approaches to further elucidate the complexities of sprint mechanics. In conclusion, while the study contributes valuable insights into the reliability and associations of kinematic variables with sprint performance among elite athletes, future research should address the identified limitations and explore additional factors to enhance our understanding of sprint mechanics comprehensively.

Kinetic variables play a pivotal role in sports biomechanics, serving as essential metrics for performance optimization, injury prevention, technique refinement, equipment design, talent identification, rehabilitation, and research. By analyzing forces, torques, and power output, coaches, scientists, and practitioners can tailor training programs, identify injury risk factors, refine techniques, design optimized equipment, identify talent, guide rehabilitation, and advance scientific understanding. Future advancements in technology, such as wearable sensors and motion capture systems, combined with interdisciplinary collaboration and innovative research methodologies, hold promise for further enhancing our utilization of kinetic variables in sports, empowering athletes to achieve peak performance while minimizing the risk of injury.

5. Conclusion

This investigation explores the biomechanics of elite athletes, emphasising the major kinematic and kinetic variables affecting sprinting efficiency. Even though sprint performance data can be inconsistent at times, several kinematic variables show dependable patterns that offer important insights into sprint mechanics. The heterogeneity in short sprint performance highlights the significance of elements such as methodological rigour and consistent effort when assessing performance. However, several kinematic variables especially those associated with the first few sprint steps show remarkable dependability in spite of differences in the total sprint performance. This emphasises how important it is to look at kinematic elements in order to have a thorough grasp of sprint mechanics. Furthermore, individual variances that contradict conventional theories emphasising step length and frequency are shown by analysing the correlations between kinematic parameters and sprint performance. The intricacy of biomechanical factors on sprinting performance is highlighted by these results, indicating the necessity of individualised training and intervention techniques. All things considered, this research advances our knowledge of the biomechanics of elite athletes and provides guidance on how to best optimise training and medical interventions to enhance athletic performance. To confirm these results and investigate other factors influencing the sprinting biomechanics of elite athletes, more research is required.

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