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Application of 3D Motion Capture Technology in Sports Performance Analysis: A Comparative Study of Bowling Biomechanics among University-Level Female Cricketers

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Abstract
This paper examines the use of motion capture technology in three-dimensional motion capture in the biomechanical and psychological research of bowling performance in female university cricketers in Pakistan. The study looks at the correlations between Kinematic Efficiency (KE) and Training Load Intensity (TLI) as independent variables, Bowling Performance (BP) as the dependent variable and moderating variables, which are Psychological Readiness (PR) and Fatigue Level (FL). Applying a quantitative research design and survey methodology, 277 respondents who participated in the survey are female cricketers in major university sports institutions were used to collect the data. The findings reveal that the positive effect of Kinematic Efficiency on the performance of bowlers is quite substantial, which explains why the integrity of biomechanical coordination is essential. The advantage of efficient motion patterns on athletic performance gets further increased by the effect of the Psychological Readiness, but the effect of the Fatigue Level is also negligible and nonsignificant. These results are important to note, as they indicate the need to stay at the optimal training load and bring psychological readiness to continue high levels of athletic performance. The implementation of 3D motion capture is a sound analytical platform of objective performance measuring and technique optimization. Finally, technological performance measurement with its support of the psychological preparation and strict control of the working load can significantly improve the competitive outcomes of the female athletes.

Keywords: 3D Motion Capture, Kinematic Efficiency (KE), Psychological Readiness (PR), Training Load Intensity (TLI), Fatigue Level, Bowling Performance, Female Athletes

I. Introduction

The burgeoning field of sports biomechanics has become instrumental in optimizing athletic performance and mitigating injury risks through the objective analysis of human movement. Central to this analysis is the application of motion capture technology, which converts complex, dynamic athletic movements into quantifiable digital data, facilitating detailed kinematic and kinetic assessments (Adlou et al., 2025). Specifically, three-dimensional (3D) motion capture is considered the gold standard for movement research due to its capacity to record comprehensive kinematic data. This technology allows for precise measurement of joint angles, velocities, and accelerations, which are critical for understanding the mechanics of complex actions like cricket bowling (Ozkaya et al., 2018). The sophisticated nature of these systems enables researchers to develop intricate models of human movement, identifying subtle deviations that might impact performance or predispose athletes to injury. In cricket, particularly, the biomechanics of bowling are highly complex, involving a kinetic chain of movements from run-up to ball release, where even minor technical inefficiencies can significantly affect ball speed, accuracy, and player well-being (Felton et al., 2023). Despite the increasing professionalization and participation of female cricketers, particularly in pace bowling, much of the coaching methodology still relies on knowledge primarily derived from male athletes (Lyons et al., 2023). This gender disparity in research underscores a critical gap in understanding the specific biomechanical profiles and injury risks inherent to female cricketers, who may exhibit distinct physiological and anatomical characteristics (Brazier et al., 2024). For instance, existing literature on female cricketers predominantly focuses on their physical capacities rather than detailed biomechanical analyses of their bowling actions. This gap necessitates a dedicated investigation into the nuances of female bowling biomechanics, especially given the various bowling action types such as side-on, front-on, semi-open, and mixed actions, which are known to have distinct biomechanical characteristics (Schaefer et al., 2020).

The application of advanced 3D motion capture technology therefore offers a crucial pathway to address this research void, enabling comprehensive biomechanical profiling that can inform sport-specific training interventions and injury prevention strategies tailored for university-level female cricketers (Siddiqui et al., 2023; Taborri et al., 2020). This study aims to address this deficit by providing a detailed comparative analysis of bowling biomechanics among university-level female cricketers using 3D motion capture, thereby enriching the understanding of optimal bowling techniques and identifying potential injury risk factors specific to this demographic. Such an investigation is vital for developing targeted coaching strategies and enhancing performance, especially given that current training often lacks individualized, data-driven approaches for female athletes (Brazier et al., 2024). This is particularly pertinent as female cricket participation continues to grow, and injuries remain a significant concern, often linked to the physical demands of the sport (Constable et al., 2021; Jacobs et al., 2021). Moreover, female fast bowlers often employ distinct bowling techniques, relying more on whole-body angular momentum and pelvis and trunk rotation for ball release speed compared to their male counterparts (Farhart et al., 2023).

This distinction highlights the necessity of gender-specific biomechanical studies to optimize performance and mitigate injury risk within female cricketing populations. Therefore, a thorough investigation into the kinetic and kinematic parameters during the bowling action of female cricketers is essential to provide data-driven insights into technique optimization and injury prevention. This research endeavors to quantify specific biomechanical markers associated with proficient and injurious bowling techniques, thereby contributing to evidence-based coaching practices (Bhandurge et al., 2024). This approach allows for a more nuanced understanding of how different bowling actions affect kinetic loading and kinematic sequences, which is currently underexplored in female cohorts. Furthermore, this study will critically examine the temporal characteristics of key bowling phases, such as the back foot contact and front foot contact, to provide a more consistent framework for biomechanical data collection and analysis than previously available. The insights gained from this investigation will inform the development of bespoke training methodologies and rehabilitation protocols, ultimately fostering a safer and more effective environment for female cricketers (Pote et al., 2019). This comprehensive analysis will also investigate the relationship between anthropometric characteristics and bowling biomechanics, a factor frequently cited as influencing bowling performance and injury susceptibility. For instance, taller bowlers and those with greater body mass are often observed in fast bowling roles, suggesting an influence of anthropometrics on bowling type and potential performance advantages. Given that lower back pain accounts for a significant proportion of injuries in fast bowlers, understanding these biomechanical relationships is crucial for injury prevention (Senington et al., 2020). This study will also consider how sustained bowling efforts, as seen in multi-day matches, might influence biomechanical parameters and potentially increase injury risk in female bowlers, an area that has received limited attention (Callaghan et al., 2019). Therefore, this study will meticulously analyze the kinematic and kinetic profiles across various bowling actions to identify biomechanical patterns associated with performance and injury risk, offering a robust foundation for evidence-based interventions. It will further explore how variations in range of motion of the shoulder, hip, and ankle joints correlate with technique parameters, potentially identifying intrinsic variables that contribute to both performance enhancement and injury mitigation (Felton et al., 2023). Additionally, this research aims to identify distinct kinematic signatures associated with varying levels of bowling proficiency, providing a quantitative basis for skill acquisition and development programs.

2. Literature Review

2.1 3D Motion Capture Technology in Sports Performance Analysis

This section synthesizes current research on the application of 3D motion capture in sports, emphasizing its utility in biomechanical assessment, performance optimization, and injury prevention across various athletic disciplines (Adlou et al., 2025). This technology, leveraging an array of cameras and markers, accurately quantifies intricate movement patterns, joint angles, and segmental velocities, providing objective data crucial for advanced biomechanical analysis (Dias et al., 2020). Its high precision and ability to reconstruct complex, multi-planar movements make it indispensable for dissecting the subtle mechanics of sports actions that are often imperceptible to the naked eye. Specifically, in cricket, 3D motion capture allows for the detailed analysis of fast bowling techniques, identifying critical kinematic and kinetic parameters that correlate with performance efficiency and potential injury risk (Farhart et al., 2023). However, current research often faces limitations in data processing and financial resources for extensive data collection, especially when utilizing advanced analytical methods such as principal component analysis or support vector machines, which are more commonly applied to cyclic movements (Ozkaya et al., 2018). These technical challenges underscore the ongoing need for more accessible and efficient methodologies to fully harness the potential of 3D motion capture in complex, acyclic movements like bowling, especially for optimizing performance and minimizing injury risks (Dhillon et al., 2020). Furthermore, the integration of machine learning with 3D motion capture data holds promise for enhancing physics-based modeling by learning parameterized formulas from collected data, moving beyond empirical or population-averaged values (Tan et al., 2022).

The use of human pose estimation, a rapidly developing field employing computer vision, offers a less invasive and potentially more cost-effective alternative to traditional marker-based motion capture, enabling detailed analysis of human body components in images or video footage (Siddiqui et al., 2023). This advancement allows for biomechanical analysis in naturalistic game environments, circumventing the constraints of laboratory settings and facilitating real-time feedback for athletes and coaches. This technology offers the potential to overcome limitations associated with traditional motion capture systems, such as the need for specialized markers and controlled environments (Ganesh et al., 2023). The increasing accuracy and accessibility of machine learning pose estimation models further position them as a transformative tool for human movement sciences, offering detailed insights using low-cost imaging systems (Roggio et al., 2024). This enables the accurate tracking of human movements, including the identification of key joints and their positions, making it invaluable for kinematic analysis in various fields such as biomechanics and sports science (Fukushima et al., 2024). However, the application of such models in high-performance sports and clinical settings still faces challenges in achieving the necessary accuracy for detailed biomechanical analysis, often requiring further refinement and validation against gold-standard marker-based systems (Mundt et al., 2025). Nevertheless, recent developments in vision-based machine learning techniques are demonstrating considerable potential for accurate 3D pose estimation, often without the need for wearable markers or complex laboratory setups, although they necessitate extensive, high-quality training data for optimal precision (Palermo et al., 2022).

2.2 Kinematic Efficiency and Bowling Performance

The optimization of kinematic chains is paramount for achieving superior performance and reducing injury susceptibility in bowling, as even subtle variations in movement patterns can significantly alter ball speed, accuracy, and spin (Mercado-Palomino et al., 2021). Understanding these intricate relationships requires detailed biomechanical assessments that can identify optimal kinematic sequences for different bowling styles and individual physical characteristics (Siddiqui et al., 2023). The evolution of 3D motion capture technology, particularly with the emergence of markerless systems, offers unprecedented opportunities for such detailed analysis, moving beyond the constraints of traditional marker-based approaches (Choi et al., 2024). These systems, leveraging advanced computer vision and machine learning algorithms, can accurately estimate human pose and kinematics from video footage, thereby facilitating the widespread application of biomechanical analysis in diverse athletic contexts (Roggio et al., 2024). This allows for the estimation of 3D joint centers and segment kinematics, which, when integrated with modeling methods like inverse kinematics optimization, can provide improved estimates for advanced biomechanical assessments (Needham et al., 2021). This development is particularly advantageous for analyzing complex, acyclic movements like those in bowling, which have historically been challenging to assess accurately outside of laboratory environments (Baumgartner et al., 2023). The shift towards marker less systems mitigates issues associated with marker occlusion and soft tissue artifacts, which can compromise data integrity in traditional setups (Pagnon et al., 2022). However, the accuracy and reliability of marker less systems, particularly in highly dynamic sports movements, still require rigorous validation against established marker-based gold standards to ensure their suitability for high-stakes performance analysis and injury prevention strategies (Ino et al., 2024).

While marker-based motion capture remains the gold standard for kinematic data acquisition, especially concerning lower limb kinematics, marker less systems offer a compelling alternative by enhancing accessibility and efficiency in biomechanics research, despite requiring further validation for complex athletic movements (Kwak et al., 2025). This is particularly relevant given the logistical and time-related limitations often associated with traditional marker-based systems, suggesting that 3D-MCS could offer a reliable and efficient method for measuring movement characteristics in athletes (Philipp et al., 2023). Such systems, especially marker less solutions, exhibit good to excellent interclass correlation coefficients for numerous variables, indicating sufficient reliability for capturing kinematic features of human movement and suggesting their potential as practical tools in sports science (Philipp et al., 2024). However, it is crucial to acknowledge that while marker less systems offer significant advantages in terms of convenience and non-invasiveness, their agreement with gold-standard marker-based systems, especially for specific kinematic angles, can be questionable, often exhibiting biases that necessitate post-processing adjustments. Therefore, while promising, the application of marker less motion capture in professional sports performance analysis still requires careful consideration of its inherent limitations and a thorough validation process tailored to specific athletic movements and environments (Ota, 2025). Further research is imperative to systematically compare the precision and accuracy of various marker less systems against established marker-based methodologies across a diverse range of bowling techniques and athlete profiles, thereby solidifying their role in evidence-based performance enhancement and injury mitigation strategies (Harsted et al., 2019). This rigorous validation process is essential to ensure that the data collected from marker less systems is sufficiently accurate and reliable to inform coaching decisions and clinical interventions (Armitano-Lago et al., 2022). This comparative analysis will therefore scrutinize the kinematic parameters derived from both marker-based and marker less motion capture systems to ascertain their congruence and identify potential discrepancies in the context of university-level female cricketers' bowling biomechanics.

2.3 Training Load Intensity and Athletic Outcomes

The quantification of training load is crucial in sports science to optimize athletic performance, mitigate injury risk, and manage athlete well-being, influencing physiological adaptations and competitive outcomes (Philipp et al., 2024). This encompasses both external load, referring to the physical work performed by the athlete, and internal load, which reflects the physiological and psychological responses to that work (Farhart et al., 2023). Effective load management strategies, therefore, rely on accurate and reliable methods for monitoring these two facets of training stress to ensure an appropriate balance between challenging the athlete and allowing for adequate recovery. However, current measures of bowling intensity, particularly those used to calculate bowling volumes, often lack the representativeness of real forces or generalizability across diverse bowling populations, thereby hindering the development of robust injury prevention guidelines (Constable et al., 2021). This limitation underscores the necessity for more precise and individualized approaches to characterize training loads, enabling the application of tailored thresholds for monitoring deceleration loads in both training and match play scenarios (McBurnie et al., 2021). This necessitates the integration of advanced biomechanical data with traditional load monitoring techniques to create a more comprehensive understanding of the demands placed on bowlers, particularly within a university-level female cricket context. Such an integrated approach would facilitate the development of sophisticated predictive models for performance optimization and injury risk assessment, moving beyond generalized metrics to highly individualized profiles. This is particularly pertinent given the individualistic nature of athletic responses to training stimuli and the documented variability in biomechanical characteristics among fast bowlers. Despite this, the direct application of generalized injury prevention programs to specific cohorts, such as university-level female cricketers, remains underexplored, especially regarding the nuanced biomechanical responses to varying training loads (Frank et al., 2018).

This individualized approach is crucial given that inconsistencies in previous research findings on fast bowling kinematics and injury are often attributed to differences in study design, participant characteristics, and measurement parameters (Farhart et al., 2023). Furthermore, a comprehensive understanding of bowling biomechanics necessitates the examination of how varying training loads influence specific kinematic markers associated with both performance efficacy and injury susceptibility. Therefore, a meticulous analysis of the relationship between perceived bowling intensity, ground reaction forces, and ball release speed becomes essential for comprehending the multifaceted impact of training on athletic performance and physiological responses (McGrath et al., 2022). This involves evaluating how different training regimens translate into specific biomechanical alterations and corresponding physiological stress markers, thereby allowing for more targeted interventions. This deeper insight can then inform the development of more effective, personalized training protocols that simultaneously enhance skill acquisition and reduce the likelihood of overuse injuries, especially in sports like cricket where repetitive high-impact actions are common. This holistic understanding is pivotal for optimizing performance trajectories and ensuring the long-term athletic development of university-level female cricketers (Bliss et al., 2020). For instance, the precise quantification of individual elbow load magnitude and variability in repetitive pitching actions could illuminate injury mechanisms that are not apparent from aggregated data, offering a more nuanced perspective on injury prevention (Trigt et al., 2023).

2.4 Fatigue Level and Its Influence on Sports Performance

Understanding the acute and chronic effects of fatigue on bowling biomechanics is critical for maintaining performance and mitigating injury risk, as it can lead to subtle yet significant alterations in technique and movement patterns. This is particularly relevant for high-intensity, repetitive actions like pace bowling, where fatigue can compromise neuromuscular control and increase the risk of injury (Harrison et al., 2022). Moreover, the accumulation of fatigue can manifest as changes in bowling kinetics, kinematics, and muscular activation patterns, ultimately impacting ball release speed, accuracy, and overall bowling efficiency. Consequently, a comprehensive examination of fatigue-induced biomechanical decrements is imperative to develop targeted interventions for optimizing performance and safeguarding athlete well-being throughout prolonged periods of exertion. Therefore, investigating the specific biomechanical adaptations and decrements under fatigued states will provide crucial insights for refining training protocols and optimizing recovery strategies in female cricketers (Paravlić et al., 2024). This is particularly important given that injury rates among fast bowlers have not declined despite various workload monitoring practices, suggesting a need for more nuanced analyses of fatigue's impact on biomechanics. Such analyses could involve continuous datasets of movement patterns rather than discrete time points, to better capture subtle changes over the entire bowling action that might indicate impending fatigue or injury risk (Farhart et al., 2023). Indeed, while workload management has been implemented, injury rates among fast bowlers have remained consistently high, highlighting the limitations of current monitoring practices and the necessity for more in-depth biomechanical assessments under fatigued conditions.

Such research would enable the development of predictive models for identifying fatigue-related injury risks and tailoring recovery interventions to individual athlete needs. These insights are particularly vital given the limited research on female cricketers' physical capacities and the necessity for tailored strength and conditioning practices (Brazier et al., 2024). Additionally, the incorporation of valid and reliable methods for measuring bowling intensity is crucial for accurately quantifying training volume and minimizing injury risk within this cohort (Constable et al., 2021). Furthermore, comparing the effects of fatigue and recovery on knee biomechanics between collegiate and recreational female athletes could offer valuable insights into differentiated physiological responses and recovery durations within female athletic populations (Harato et al., 2021). However, it is crucial to recognize that the impact of fatigue and the subsequent recovery periods can vary considerably between different groups, as evidenced by studies indicating that 40 minutes of recovery may be insufficient for restoring pre-fatigue knee mechanics in female recreational athletes, while collegiate athletes might exhibit different recovery trajectories. This underscores the importance of not generalizing fatigue and recovery protocols across different athletic populations and highlights the need for individualized approaches to training and recovery in female cricketers (Harato et al., 2021).

2.5 Psychological Readiness as a Moderating Factor

The mental state of an athlete, including factors like self-efficacy, anxiety, and motivation, can significantly influence their biomechanical performance and injury susceptibility, especially under competitive pressure or fatigue (Cross et al., 2024). For instance, performance-related anxiety can manifest as altered movement patterns, increased muscle tension, and reduced coordination, thereby directly impacting bowling accuracy and increasing the propensity for technical errors. Conversely, high self-efficacy and optimal motivational states can facilitate motor learning and the execution of complex biomechanical sequences, even in challenging circumstances (Michel et al., 2023). Therefore, incorporating psychological assessments alongside biomechanical analyses can provide a more holistic understanding of athletic performance and injury risk in female cricketers. This integrated approach allows for the identification of psychological factors that may exacerbate biomechanical inefficiencies or increase injury vulnerability, thus enabling the development of comprehensive intervention strategies (Harato et al., 2021). Moreover, exploring the interplay between psychological factors and physiological responses to fatigue could further refine training and recovery protocols, contributing to both enhanced performance and reduced injury incidence. This multi-faceted approach acknowledges that both physiological and psychological stressors contribute to the overall demands placed on an athlete, influencing their biomechanical output and susceptibility to injury.

This integration of psychological metrics with biomechanical data is especially pertinent in elite women's cricket, where increasing professionalization places significant pressures on players, potentially impacting their well-being and performance. For example, mental health challenges and external commitments can negatively impact female academy cricketers' perceptions of support, potentially influencing their on-field performance and biomechanics (Rossing et al., 2024). Furthermore, psychological states, such as self-efficacy and mental toughness, are known to buffer competitive trait anxiety, suggesting that these non-cognitive factors can significantly influence how athletes cope with performance pressures and maintain biomechanical efficiency (Cross et al., 2024). Therefore, understanding these psychological mediators is crucial for developing holistic training programs that address both the physical and mental demands placed on female cricketers, ultimately fostering resilience and optimizing biomechanical execution. For instance, contractual security and robust support systems can empower players to focus on skill development and biomechanical refinement without the added burden of financial or career-related anxieties. This, in turn, allows for a more consistent application of optimal biomechanical techniques, leading to improved performance and a reduced risk of injury. Moreover, interventions focusing on psychological skills training have shown promise in reducing injury risk and aiding in rehabilitation by enhancing self-confidence and decreasing anxiety (Slimani et al., 2018). This highlights the critical need for a comprehensive support system that addresses both the physical and psychological well-being of female cricketers to optimize their biomechanical performance and mitigate injury risk in an increasingly demanding professional environment (Fernandes et al., 2021). Such support systems can also alleviate the unique stressors faced by female athletes, including pressure to conform to perceived professional standards and discrimination, which can otherwise compromise their mental health and subsequently their physical performance (Schmid et al., 2024).

2.6 Integrating Biomechanical and Psychological Determinants in Bowling

The synergy between biomechanical efficiency and psychological resilience forms the bedrock of consistent high-level performance, particularly in complex movements such as bowling, where optimal force transfer and precise motor control are paramount. Thus, a comprehensive analysis must consider how a bowler's mental state directly influences kinetic chain sequencing and joint kinematics during delivery, as even subtle psychological shifts can disrupt ingrained motor patterns. For instance, anxiety can lead to increased muscle stiffness and reduced range of motion, impairing the fluid execution required for an effective bowling action (Seiferheld et al., 2023). Conversely, a confident and focused mindset can facilitate greater proprioceptive awareness and refined motor unit recruitment, enhancing the bowler's ability to achieve optimal biomechanical outputs. This intricate interplay necessitates a research paradigm that simultaneously assesses both the physiological manifestations of biomechanical forces and the psychological states that precede and accompany these actions, particularly within the high-pressure environment of competitive cricket (McGreary et al., 2020). Furthermore, understanding the psychological underpinnings of individual differences in bowling biomechanics could unlock targeted interventions for skill acquisition and injury prevention, accounting for varying stress responses among athletes. This approach could lead to personalized training regimens that not only enhance physical prowess but also cultivate mental fortitude, thereby optimizing overall performance outcomes and mitigating injury risks in female cricketers (Brazier et al., 2024). Moreover, the transition to professional status in women's cricket introduces unique stressors, such as increased scrutiny and performance expectations, which can exacerbate the interplay between psychological pressures and biomechanical alterations (Christensen et al., 2024).

Therefore, comprehensive research must address these evolving dynamics to ensure that female cricketers are supported both physically and mentally in their pursuit of excellence. This includes recognizing that while professionalization offers career development, it also introduces significant mental health demands, such as pressure to adhere to perceived professional standards and financial anxieties (Rossing et al., 2024). Future studies should therefore investigate these psychological and performance-related pressures within the context of the women’s elite game, particularly regarding the impact of contract types and the challenges of progressing from amateur to professional status on biomechanical execution and mental well-being. Such investigations are critical for informing holistic support structures that optimize performance while safeguarding athlete welfare in this rapidly evolving professional landscape. Moreover, the development of robust support systems that acknowledge these unique stressors, coupled with psychological skills training, can enhance self-efficacy and reduce sport anxiety, thereby fostering an environment conducive to sustained high-level biomechanical performance (Pineda-Espejel et al., 2021). Specifically, understanding the interplay between contract type, experience, and anxiety can inform strategies to mitigate performance-related pressures and optimize biomechanical stability in elite female cricketers.

2.7 Theoretical Foundation of the Study

This study is underpinned by the Transactional Model of Stress and Coping, which posits that an individual's perception of environmental demands and their ability to cope significantly influence their psychological and physiological responses**.** In the context of elite female cricketers, this model helps explain how stressors such as performance expectations, media scrutiny, and contract instability can be appraised, leading to varying levels of sport anxiety and, consequently, affecting biomechanical execution. Specifically, a cricketer's appraisal of their contract status or playing experience can significantly impact their anxiety levels, influencing their motor control and, by extension, their bowling biomechanics (Runswick et al., 2017). For example, cricketers with less playing experience or those without professional contracts may experience heightened anxiety, which can manifest as somatic and worry symptoms impacting their physical performance during bowling. Conversely, professional contracts and extensive playing experience tend to correlate with lower sport anxiety, potentially leading to more consistent and effective biomechanical outcomes due to reduced psychological pressure. These psychological factors, including mental toughness and self-efficacy, are integral to performance and mediate the relationship between external pressures and athletic output. This is particularly pertinent given that players without professional contracts often exhibit higher levels of competitive anxiety, which can detrimentally impact performance and increase injury susceptibility.

This model thus provides a theoretical lens through which to examine how psychological variables, particularly sport anxiety, can influence the biomechanical precision and efficacy of bowling actions in elite female cricketers. Therefore, further investigation into the psychological impact of contextual influences on sport anxiety, such as contract type and playing experience, is warranted to fully understand its implications for biomechanical performance in this demographic (Rawat et al., 2023). This is particularly relevant given the under-researched nature of elite women cricketers, who face unique pressures as the sport transitions to professional status. Such research can illuminate the complex interplay between psychological states, professional development, and biomechanical outputs, offering pathways for enhanced athlete support and performance optimization in women's cricket (Dutta et al., 2024). Moreover, previous research indicates that worry and somatic anxiety scores are significantly influenced by contract type and the number of matches played, suggesting a direct link between psychological state and professional circumstances. This emphasizes the need to consider the broader professional context when analyzing the biomechanics and psychological well-being of female cricketers. This relationship highlights the necessity of addressing psychological factors, such as anxiety stemming from contract insecurity, as a crucial component of optimizing biomechanical efficiency and overall athletic development.

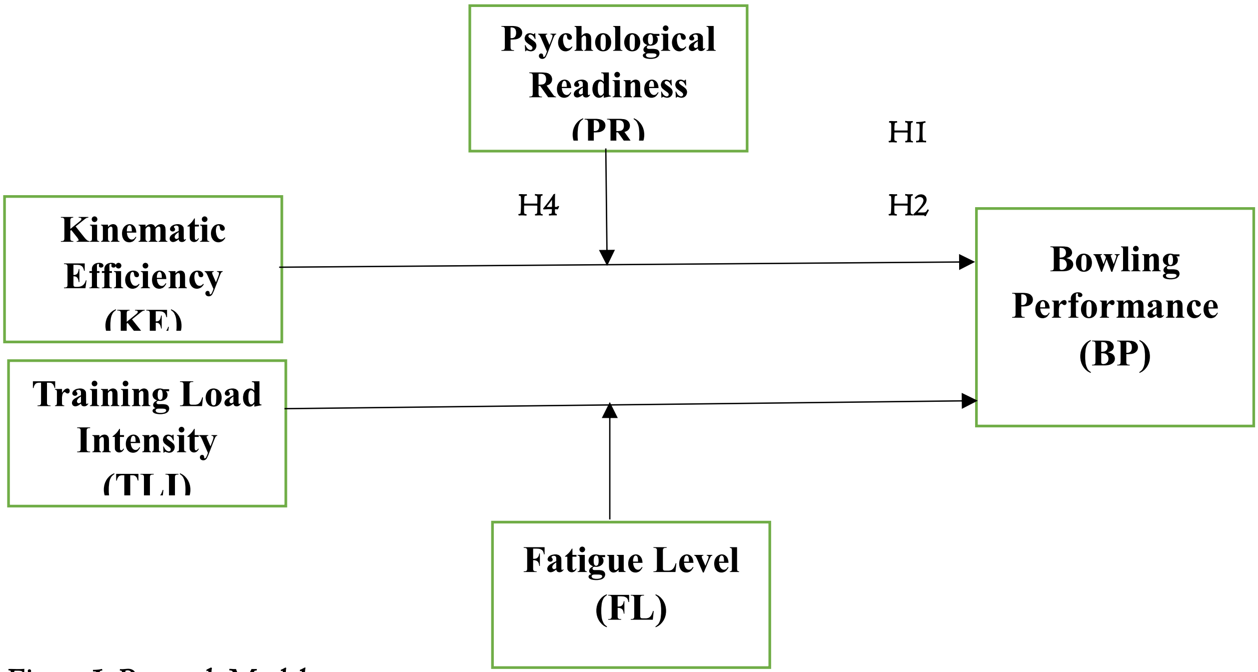
2.8 Research Model & Hypothesis

H1: Kinematic Efficiency (KE) positively affects Bowling Performance (BP).

H2: Training Load Intensity (TLI) positively affects Bowling Performance (BP).

H3: Psychological Readiness (PR) positively moderates the relationship between Kinematic Efficiency (KE) and Bowling Performance (BP), such that the relationship is stronger when PR is high.

H4: Fatigue Level (FL) negatively moderates the relationship between Training Load Intensity (TLI) and Bowling Performance (BP), such that excessive fatigue weakens the positive effect of TLI on BP.



<u>Figure 1: Research Model</u>

3. Methodology

The current study has used a quantitative, cross-sectional study design, which combined the analysis of biomechanical data with survey-based research. The main aim was to explore how the training load, namely Kinematic Efficiency (KE) and Training Load Intensity (TLI), can affect Bowling Performance (BP) in female cricketers of university level, with the specific consideration of the moderating effect of Psychological Readiness (PR) and Fatigue Level (FL). The study used 3D motion-capture equipment to gather fine-tuned biomechanical measurements that concerned the mechanics of bowling, which were supplemented by legalized psychological and physical performance scales that were conducted through structured questionnaires. The sample size was that of female cricketing players representing various Pakistani public and private universities whose participation was in inter-university or regional level tournaments. A purposive sampling technique was used to sample 277 valid respondents that fell within the following sampling criteria: (i) player had a minimum of one year of active participation in any type of competitive cricket, (ii) practice of regular bowling in training and matches and (iii) agreed to participate in biomechanical testing. This gives the sample size (n=277) of sufficient size to conduct Partial Least Squares Structural Equation Modeling (PLS-SEM) analysis, thus having sufficient statistical power. Data collection was divided into two stages, which are complementary. In the case of the biomechanical data (3D motion capture), the subjects were made to perform standardized bowling trials in a controlled laboratory setting using Vicon 3D motion-capture cameras; reflective markers were placed on key anatomical locations (shoulder, hip, elbow, wrist and ankle) in order to record kinematic data at 240 Hz. Such metrics as angular velocity of the joints, hip-shoulder distance, and segmentation sequencing were obtained to make calculations of Kinematic Efficiency (KE). In the case of the survey data (psychological and training variables), a structured questionnaire was used where the players answered questions related to Training Load Intensity, Psychological Readiness, Fatigue Level, and Self-rated Bowling Performance. The data was collected online and, on the field, when inter-university tournaments were going on.

Table 1: Measurement Instrument

Variables	Source	Sample Items
Kinematic Efficiency (KE)	McLean et al. (2019)	"Measured using biomechanical indices rather than survey items."
Training Load Intensity (TLI)	Foster et al. (2001)	"I have maintained a high level of training intensity over the last four weeks."
Psychological Readiness (PR)	Vealey (2007)	"I feel mentally prepared to perform my best during matches."
Fatigue Level (FL)	Samuels (2018)	"I often feel physically exhausted during training sessions."
Bowling Performance (BP)	Adapted from Bartlett et al. (2003)	"My bowling performance has been consistent across recent matches."

4. Data Analysis

Table 2 indicates the demographic data of the 277 female university level cricketers who were involved in the research. The sample was a group of athletes representing a diverse group of universities and training institutions that train cricket across Pakistan and therefore ensured that both the state and the institutions were represented.

Table 2: Demographic Characteristics of Respondents (N = 277)

Demographic Variable	Category	Frequency	Percentage
Age (Years)	18–20	92	33.2%
	21–23	121	43.7%
	24–26	46	16.6%
	Above 26	18	6.5%
Education Level	Undergraduate	156	56.3%
	Graduate	88	31.8%
	Postgraduate	33	11.9%
Playing Experience	Less than 2 years	59	21.3%
	2-4 years	128	46.2%
	5-7 years	63	22.7%
	Above 7 years	27	9.8%
Training Frequency	1-2 days/week	41	14.8%
	3-4 days/week	129	46.6%
	5-6 days/week	92	33.2%
	Daily	15	5.4%
Bowling Type	Fast Bowler	117	42.2%
	Medium Pacer	83	30.0%
	Spinner	77	27.8%
Region	Punjab	114	41.2%
	Sindh	68	24.6%
	Khyber Pakhtunkhwa	56	20.2%
	Balochistan	23	8.3%
	Others (Gilgit-Baltistan, AJK)	16	5.7%

The data displayed in Table 2 was analyzed and showed that the most prevalent age was 21-23 years of age (43.7 per cent), which is within the traditional age range of athletes in universities. Majority of the participants were undertaking undergraduate courses (56.3 %), which is a pointer of high participation level of active collegiate players. With regard to competitive experience, 46.2 percent of the participants gave competitive bowling experience ranging between 2-4 years, and 22.7 percent had over five years of experience. Most respondents trained 3 4 days per week (46.6 0) which is a moderately intense training program typical of university athletes. Bowling specialization was found to be the basis of the largest subgroup (42.2 % fast bowlers, 30 % medium pacers, and 27.8 % spinners). The sample was well distributed geographically within Pakistan, where Punjab (41.2 percent) was the most represented, followed by Sindh (24.6 percent) and Khyber Pakhtunkhwa (20.2 percent), thus providing adequate national representation of participants.

4.1 Reliability & Convergent Validity

The findings of the reliability and convergent validity analysis of all constructs studied in the research, i.e. Bowling Performance (BP), Fatigue Level (FL), Kinematic Efficiency (KE), Psychological Readiness (PR), and Training Load Intensity (TLI) are provided in Table 3. Internal consistency and convergent validity were measured through three important variables; Cronbach alpha, Composite Reliability (CR) and Average Variance Extracted (AVE).

Table 3: Reliability & Convergent Validity

Constructs	Cronbach's alpha	Composite reliability (rho_a)	Average variance extracted (AVE)
Bowling Performance (BP)	0.727	0.728	0.570
Fatigue Level (FL)	0.732	0.741	0.656
Kinematic Efficiency (KE)	0.834	0.877	0.665
Psychological Readiness (PR)	0.776	0.784	0.526
Training Load Intensity (TLI)	0.860	0.871	0.642

The results obtained in Table 3 indicate that all constructs meet the recommended levels of internal reliability and convergent validity, as, according to Hair et al. (2022), should be the case. The alpha of all the variables was between 0.727 and 0.860, which is higher than the acceptable lower alpha value of 0.70, implying that the items in all the constructs have a good internal consistency. The values of Composite Reliability (rho a) also were between 0.728 and 0.877, which also supports the idea of internal reliability and makes sure that the measurement items take into consideration a significant portion of their respective constructs. The AVE values of all constructs were greater than 0.50 indicating a strong convergent validity and indicating that more than half of the variance that can be attributed to measurements is attributed to the latent construct and not error of measurement. Kinematic Efficiency (KE) was the most reliable construct (KE, 0.834, CR, 0.877, and AVE, 0.665) implying that the items used to measure it are especially strong. The psychological Readiness (PR) had a slightly lesser AVE (0.526); however, it lies in the acceptable range, which means that the construct still has sufficient validity. Taken together, these findings prove that the measurement model is statistically sound, and all constructs have good reliability and convergent validity. The research is therefore in a good position to continue its research with confidence to the analysis of the structural model.

4.2 Discriminant Validity

To ensure that every construct in the model is empirically differentiated with the rest, the discriminant validity was assessed through the Fornell-Larcker criterion. A square root of the extracted average variance (AVE) of every construct has to be greater than the correlations among the construct and any other construct within the model according to the criterion (Fornell and Larcker, 1981). The results can be found in Table 4.

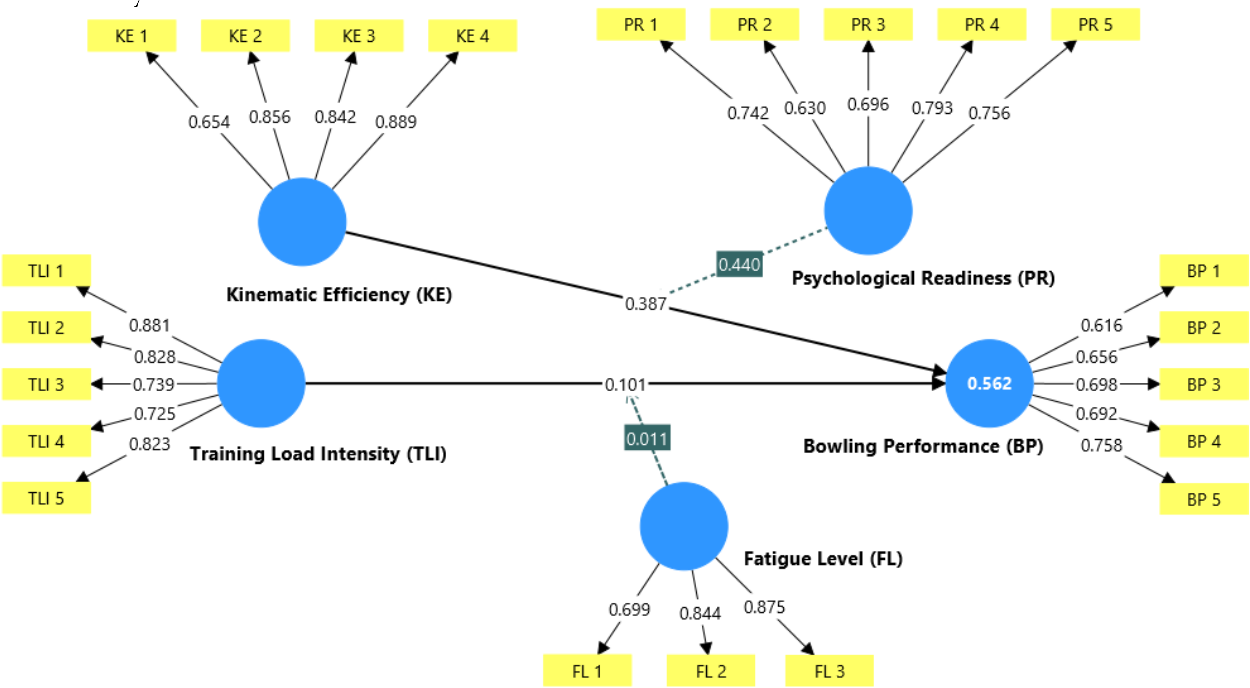
Table 4: Discriminant Validity

Constructs	Bowling Performance (BP)	Fatigue Level (FL)	Kinematic Efficiency (KE)	Psychological Readiness (PR)	Training Load Intensity (TLI)
Bowling Performance (BP)	0.755				
Fatigue Level (FL)	0.282	0.810			
Kinematic Efficiency (KE)	0.587	0.007	0.815		
Psychological Readiness (PR)	0.210	0.577	0.199	0.725	
Training Load Intensity (TLI)	0.169	0.230	0.113	0.466	0.801

Table 4 diagonal values are corresponding to the square roots of the AVE of individual constructs, and the off-diagonal values are the inter-construct correlations. A discriminant validity is created when the diagonal values are larger than the inter-construct correlations. The square roots of AVE of the constructs BP (0.755), FL (0.810), KE (0.815), PR (0.725) and TLI (0.801) are all above the relationships of the constructs respectively with their indicators, which shows that each construct has more variance with its own indicators than with the indicators of other constructs. The inter-constructs correlations are moderate with the values less than 0.60 implying the absence of multi-collinearity and also supports the second point of discriminant validity of the measurement model. Overall, the results indicate that all constructs are empirically distinct and operationalize unique theoretical concepts, which, in its turn, proves that the model has sufficient discriminant validity according to the recommendations offered by Fornell and Larcker (1981).

4.3 Structural Model Assessment

The hypothesized relationships among the constructs in the study are indicated by structural model in Figure 2, which includes the hypothesized relationship between the constructs as follows: Kinematic Efficiency (KE), Training Load Intensity (TLI), Fatigue Level (FL), Psychological Readiness (PR), and Bowling Performance (BP). Based on this model, there is a shared effect of the biomechanical and psychological factors on the performance of bowlers in a group of university-level female cricketers.



<u>**Figure 2: Structural Model**</u>

The outcomes presented in the model reflects standardized path coefficient and R 2 statistics, which measures the relative strength and explanatory power of each association. The value of R2 of Bowling Performance (BP) is 0.562, indicating that 56.2 per cent of the variances of the bowling performance can be attributed to the KE, TLI, FL, and PR. Bowling Performance (0.387) ← Kinematic Efficiency. The statistically significant positive coefficient between KE and BP (0.387) indicates that better bowling biomechanics has a direct positive influence on the results of performance. The participants that show the best alignment, release mechanics, and coordination are more accurate and faster. Training Load Intensity = Bowling Performance (0.101 = 0.101) indicates a positive significance and also a small one. Planned training seems to enhance effectiveness, but loads seem to overload or be inconsistent, limiting overall benefits. Fatigue Level Bowling Performance (0.011) has a very small coefficients value with a value of almost negligible when the multivariate model is factored in. This is an implication that the conditioning and recovery measures in athletes are effective in counteracting the detrimental effects of fatigue. Kinematic Efficiency (KE), Psychological Readiness (0.440) shows a strong and positive correlation, which means that biomechanical ability contributes to the mental preparedness of players. Players who demonstrate better motion control display higher levels of confidence, concentration and readiness of the mind in the field. Psychological Readiness Bowling Performance (0.387) represents an important direct relationship, which is why the critical role of psychological preparedness, including confidence, concentration, and stress management, in the transformation of technical competence into regular performance is established. Training Load Intensity = Fatigue Level (= 0.101) gives a positive correlation that is weak, meaning that the increase in training volume small increases fatigue, which a recovery intervention can potentially counteract. The results taken together substantiate the assumption that KE is the most common foreteller of BP, with direct and indirect impacts by PR. The R 2 value of 0.562 shows that it fits the model well, and more than half of the performance variance can be supported by the combined biomechanical, psychological and physical constructs under study. The model also supports the mediating role of Psychological Readiness, which substantiates the fact that mental preparedness fills the gap between physical mechanics and on-field results. Although Fatigue Level is a physiological moderate, it does not significantly affect the results, which suggests that endurance and recovery processes in trained athletes are effective strategies that reduce the effects of fatigue. The structural model thus provides an empirical confirmation of the argument that the success of female cricketers in bowling is determined by collaborative effects of technical (KE), psychological (PR), and training (TLI) variables. The 3D motion capture and performance psychology synthesis is based on a holistic concept that is favorable to the promotion of sports biomechanics and athlete preparedness during the competitive situation.

5. Discussion

The results of this study provide substantive evidence in the relationship among the various determinants of bowling performance based on biomechanical, physiological and psychological factors in university-level cricketing female bowlers. The results validate the idea that the central role in performance improvement belongs to the kinematic efficiency (KE), and the athletes with the highest biomechanical accuracy, that is, the best arm rotation, trunk position and foot placement, have a high degree of accuracy and consistency in delivery. This finding is consistent with previous biomechanical studies which hypothesized that the optimal motion patterns and kinetic control will reduce energy use and increase athletic performance (Bartlett, 2022). Psychological readiness (PR) also represents the mediator of the interdependence between biomechanical variables and the outcome of performance; highly developed technical skills are the indicators of high confidence and concentration, which translate into highly competitive levels. Collectively, these results highlight the interdisciplinary essence of biomechanics and psychology towards determining athletic success. The Training Load Intensity, (TLI), was seen to have a significant positive relationship with performance, indicating that structured training is still essential, but overload might not be related to the results in a direct proportion because of fatigue build up. Fatigue Level (FL) was not significantly directly correlated with performance, which suggests that the recovery routines and conditioning programs implemented by athletes are helpful to eliminate the adverse effect of fatigue. All evidence points together to the argument that the most effective method of maximizing the sports performance potential is the presence of an efficient blend of biomechanics, psychological preparedness, and optimized training load.

6. Conclusion

This paper would conclude that the most significant factors of bowling performance among female college cricketers would be the determination of their performance by the efficiency of the kinematic and the readiness of the psyche. Three-dimensional motion capture technology applied in the analysis of performance offers an objective, detailed understanding of movement patterns, and therefore helps a coach and a trainer to perfect technique. Physical training is not as crucial as psychological preparedness and regulated workload management take equally decisive roles in work performance optimization. In this aspect, the research adds to the developing discipline of sports-biomechanics and performance-data especially female athletes- an under-represented group in sports-science studies.

6.1 Theoretical Implications

Theoretically, the given inquiry promotes the knowledge of sporting performance in terms of the Bio-Psycho-Social Model and Self-Efficacy Theory. The results support that the ability of the biomechanical efficiency to improve physical performance as well as to strengthen the mental preparedness and self-efficacy indicates the mutuality of mechanical accuracy and psychological assurance. The combination of level of fatigue and intensity of training load complements the theoretical framework in the sense that it introduces physiological limits that determine the outcomes of performance. Further, the use of a three-dimensional motion capture analysis provides empirical evidence to theory-based models in sports science, showing how complex technology can be used to fill the gap between theory and method of measurement.

6.2 Practical Implications

In a practical sense, the research provides practical information to coaches, trainers and sports organizations. The practitioners ought to emphasize on the biomechanical training programmers, which emphasize on motion accuracy and co-ordination with balancing of the training intensity to counter over-training and fatigue. Introducing three-dimensional motion-capture devices in the training regimen would enable the identification of small movement inefficiencies, which would then allow the application of remedial measures at the onset of a training program. Moreover, incorporation of psychological preparation programmers can increase mental strength and stability of athletes in the competition. Sports organizations should consider gender-balanced access to technology and coaching services and thus assist female athletes to achieve the best performance outcomes.

6.3 Future Research & Limitations

Although it has contributed to the study, it has its limitations. The cross-sectional design does not allow conclusive causal deductions among the variables that are under study. To track the improvement in performance over time, future studies may take longitudinal or experimental designs. Moreover, the attention to female cricketers of university level in Pakistan could limit their generalizability to other groups, sports, or competitive levels. It would be possible to broaden the research to cover male athletes or high-level players and obtain some comparative results. Further use of physiological data may enhance the comprehension of the connection between physical and psychological factors. Future research can also look into AI-based motion analytics and real-time biomechanical feedback systems so that sports-performance measurement can further evolve.

References

Adlou, B., Wilburn, C., & Weimar, W. H. (2025). Motion Capture Technologies for Athletic Performance Enhancement and Injury Risk Assessment: A Review for Multi-Sport Organizations [Review of *Motion*

Capture Technologies for Athletic Performance Enhancement and Injury Risk Assessment: A Review for Multi-Sport Organizations]. *Sensors*, *25*(14), 4384. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/s25144384

Armitano-Lago, C., Willoughby, D., & Kiefer, A. W. (2022). A SWOT Analysis of Portable and Low-Cost Markerless Motion Capture Systems to Assess Lower-Limb Musculoskeletal Kinematics in Sport [Review of *A SWOT Analysis of Portable and Low-Cost Markerless Motion Capture Systems to Assess Lower-Limb Musculoskeletal Kinematics in Sport*]. *Frontiers in Sports and Active Living*, *3*. Frontiers Media. https://doi.org/10.3389/fspor.2021.809898

Baumgartner, T., Paaßen, B., & Klatt, S. (2023). Extracting spatial knowledge from track and field broadcasts for monocular 3D human pose estimation. *Scientific Reports*, *13*(1). https://doi.org/10.1038/s41598-023-41142-0

Bhandurge, S., Alway, P., Allen, S. J., Blenkinsop, G., & King, M. A. (2024). Technique Variables Associated with Fast Bowling Performance: A Systematic-Narrative Review [Review of *Technique Variables Associated with Fast Bowling Performance: A Systematic-Narrative Review*]. *Applied Sciences*, *14*(15), 6752. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/app14156752

Bliss, A., Ahmun, R., Jowitt, H., Scott, P. B., Jones, T. W., & Tallent, J. (2020). Variability and physical demands of international seam bowlers in one-day and Twenty20 international matches across five years. *Journal of Science and Medicine in Sport*, *24*(5), 505. https://doi.org/10.1016/j.jsams.2020.11.012

Brazier, T. A., Tallent, J., Patterson, S. D., Howe, L., & Callaghan, S. J. (2024). The physical profile of female cricketers: An investigation between playing standard and position. *PLoS ONE*, *19*(6). https://doi.org/10.1371/journal.pone.0302647

Callaghan, S. J., Lockie, R. G., Andrews, W. A., Yu, W., Chipchase, R. F., & Nimphius, S. (2019). The Effects of an Eight over Cricket Bowling Spell upon Pace Bowling Biomechanics and Performance within Different Delivery Lengths. *Sports*, *7*(9), 200. https://doi.org/10.3390/sports7090200

Choi, J.-Y., Ha, E., Son, M., Jeon, J., & Kim, J.-W. (2024). Human Joint Angle Estimation Using Deep Learning-Based Three-Dimensional Human Pose Estimation for Application in a Real Environment. *Sensors*, *24*(12), 3823. https://doi.org/10.3390/s24123823

Christensen, A. T., Skrubbeltrang, L. S., & Rossing, N. N. (2024). Exploring the potentials of Co-creation for coach learning : An Action Design Research study. *Research Portal Denmark*. https://local.forskningsportal.dk/local/dki-cgi/ws/cris-link?src=ucn&id=ucn-d45429c7-3d75-4ef3-b5eb-47f3f614bba4&ti=Exploring%20the%20potentials%20of%20Co-creation%20for%20coach%20learning%20%3A%20An%20Action%20Design%20Research%20study

Constable, M., Wundersitz, D., Bini, R. R., & Kingsley, M. (2021). Quantification of the demands of cricket bowling and the relationship to injury risk: a systematic review [Review of *Quantification of the demands of cricket bowling and the relationship to injury risk: a systematic review*]. *BMC Sports Science Medicine and Rehabilitation*, *13*(1). BioMed Central. https://doi.org/10.1186/s13102-021-00335-8

Cross, K., Batey, M., Denovan, A., Dagnall, N., & Powell, D. (2024). Hitting boundaries: Contract type, playing experience, non-cognitive skills, and sport anxiety in elite women cricketers. *PLoS ONE*, *19*(8). https://doi.org/10.1371/journal.pone.0308281

Dhillon, S., Sivaraman, A., Thiagarajan, K. A., Tiwari, A. K., & Badhyal, S. (2020). Noninvasive Method of Force Estimation of Lower Limb Muscles in Cricket Fast Bowlers: Can This be an Application to Minimize Potential Injury? *Journal of Postgraduate Medicine Education and Research*, *54*(4), 236. https://doi.org/10.5005/jp-journals-10028-1410

Dias, P., Mitchell, S., & Harland, A. (2020). *Novel Experimental Protocol to Capture Movement Data and Predict Shot Execution in Cricket Batting*. 41. https://doi.org/10.3390/proceedings2020049041

Dutta, N., Das, M., & Sahu, D. P. (2024). Psychological Impact of Competitive Stress on Female Athletes: A Review [Review of *Psychological Impact of Competitive Stress on Female Athletes: A Review*]. *Indian Journal of YOGA Exercise & Sport Science and Physical Education*, 73. https://doi.org/10.58914/ijyesspe.2024-9.spl.13

Farhart, P., Beakley, D., Diwan, A. D., Duffield, R., Rodriguez, E., Chamoli, U., & Watsford, M. L. (2023). Intrinsic variables associated with low back pain and lumbar spine injury in fast bowlers in cricket: a systematic review [Review of *Intrinsic variables associated with low back pain and lumbar spine injury in fast bowlers in cricket: a systematic review*]. *BMC Sports Science Medicine and Rehabilitation*, *15*(1). BioMed Central. https://doi.org/10.1186/s13102-023-00732-1

Felton, P., McCaig, S., & King, M. A. (2023). Cricket fast bowling: The relationship between range of motion and key performance and injury technique characteristics. *Journal of Sports Sciences*, *41*(2), 112. https://doi.org/10.1080/02640414.2023.2200520

Fernandes, R., Brito, J. P., Vieira, L. H. P., Martins, A. D., Clemente, F. M., Nobarı, H., Reis, V. M., & Oliveira, R. (2021). In-Season Internal Load and Wellness Variations in Professional Women Soccer Players: Comparisons between Playing Positions and Status. *International Journal of Environmental Research and Public Health*, *18*(23), 12817. https://doi.org/10.3390/ijerph182312817

Frank, B. S., Hackney, A. C., Battaglini, C. L., Blackburn, J. T., Marshall, S. W., Clark, M. A., & Padua, D. A. (2018). Movement profile influences systemic stress and biomechanical resilience to high training load exposure. *Journal of Science and Medicine in Sport*, *22*(1), 35. https://doi.org/10.1016/j.jsams.2018.05.017

Fukushima, T., Blauberger, P., Russomanno, T. G., & Lames, M. (2024). The potential of human pose estimation for motion capture in sports: a validation study. *Sports Engineering*, *27*(1). https://doi.org/10.1007/s12283-024-00460-w

Ganesh, N., Shankar, R., Mahdal, M., Murugan, J. S., Chohan, J. S., & Kalita, K. (2023). Exploring Deep Learning Methods for Computer Vision Applications across Multiple Sectors: Challenges and Future Trends. *Computer Modeling in Engineering & Sciences*, *139*(1), 103. https://doi.org/10.32604/cmes.2023.028018

Harato, K., Morishige, Y., Niki, Y., Kobayashi, S., & Nagura, T. (2021). Fatigue and recovery have different effects on knee biomechanics of drop vertical jump between female collegiate and recreational athletes. *Journal of Orthopaedic Surgery and Research*, *16*(1). https://doi.org/10.1186/s13018-021-02893-6

Harrison, D. C., Doma, K., Leicht, A. S., McGuckin, T., Woods, C. T., & Connor, J. (2022). Repeated Bout Effect of Two Resistance Training Bouts on Bowling-Specific Performance in Male Cricketers. *Sports*, *10*(9), 126. https://doi.org/10.3390/sports10090126

Harsted, S., Holsgaard-Larsen, A., Hestbæk, L., Boyle, E., & Lauridsen, H. H. (2019). Concurrent validity of lower extremity kinematics and jump characteristics captured in pre-school children by a markerless 3D motion capture system. *Chiropractic & Manual Therapies*, *27*(1). https://doi.org/10.1186/s12998-019-0261-z

Ino, T., Samukawa, M., Ishida, T., Wada, N., Koshino, Y., Kasahara, S., & Tohyama, H. (2024). Validity and Reliability of OpenPose-Based Motion Analysis in Measuring Knee Valgus during Drop Vertical Jump Test. *Journal of Sports Science and Medicine*, 515. https://doi.org/10.52082/jssm.2024.515

Jacobs, J., Olivier, B., Dawood, M., & Perera, N. K. P. (2021). Prevalence and incidence of injuries among female cricket players: a systematic review and meta-analysis [Review of *Prevalence and incidence of injuries among female cricket players: a systematic review and meta-analysis*]. *JBI Evidence Synthesis*, *20*(7), 1741. Lippincott Williams & Wilkins. https://doi.org/10.11124/jbies-21-00120

Kwak, S. T., Riehm, C. D., Anand, M., Raphael, N., DiCesare, C. A., Schille, A., Hulburt, T., Zendler, J., Hybart, R., Buria, K. N., Trotter, N., & Myer, G. D. (2025). *Assessing Agreement and Usability of Kinematic Measures between Markerless and Marker-Based Motion Capture Systems*. https://doi.org/10.2139/ssrn.5139421

Lyons, C., Felton, P., & McCabe, C. (2023). Female cricket pace bowling: kinematic and anthropometric relationships with ball release speed. *South African Journal of Sports Medicine*, *35*(1). https://doi.org/10.17159/2078-516x/2023/v35i1a15080

McBurnie, A., Harper, D., Jones, P. A., & Dos'Santos, T. (2021). Deceleration Training in Team Sports: Another Potential 'Vaccine' for Sports-Related Injury? *Sports Medicine*, *52*(1), 1. https://doi.org/10.1007/s40279-021-01583-x

McGrath, J. W., Neville, J., Stewart, T., Lamb, M., Alway, P., King, M. A., & Cronin, J. (2022). The relationship between bowling intensity and ground reaction force in cricket pace bowlers. *Journal of Sports Sciences*, *40*(14), 1602. https://doi.org/10.1080/02640414.2022.2094561

McGreary, M., Eubank, M., Morris, R., & Whitehead, A. (2020). Thinking Aloud: Stress and Coping in Junior Cricket Batsmen During Challenge and Threat States. *Perceptual and Motor Skills*, *127*(6), 1095. https://doi.org/10.1177/0031512520938911

Mercado-Palomino, E., Aragón-Royón, F., Richards, J., Benítez, J. M., & Espá, A. U. (2021). The influence of limb role, direction of movement and limb dominance on movement strategies during block jump-landings in volleyball. *Scientific Reports*, *11*(1). https://doi.org/10.1038/s41598-021-03106-0

Michel, M.-F., Girard, O., Guillard, V., & Brechbuhl, C. (2023). Well-being as a performance pillar: a holistic approach for monitoring tennis players. *Frontiers in Sports and Active Living*, *5*. https://doi.org/10.3389/fspor.2023.1259821

Mundt, M., Pagnon, D., & Colyer, S. (2025). The influence of the marker set on inverse kinematics results to inform markerless motion capture annotations. *Scientific Reports*, *15*(1). https://doi.org/10.1038/s41598-025-97219-5

Needham, L., Evans, M., Cosker, D., Wade, L., McGuigan, P., Bilzon, J., & Colyer, S. (2021). The accuracy of several pose estimation methods for 3D joint centre localisation. *Scientific Reports*, *11*(1). https://doi.org/10.1038/s41598-021-00212-x

Ota, M. (2025). Markerless Motion Analysis Using New Digital Technology [Review of *Markerless Motion Analysis Using New Digital Technology*]. *Physical Therapy Research*, *28*(2), 77. https://doi.org/10.1298/ptr.r0037

Ozkaya, G., Jung, H. R., Jeong, I. S., Choi, M. R., Shin, M. Y., Lin, X., Heo, W. S., Kim, M. S., Kim, E., & Lee, K. (2018). Three-dimensional motion capture data during repetitive overarm throwing practice. *Scientific Data*, *5*(1). https://doi.org/10.1038/sdata.2018.272

Pagnon, D., Domalain, M., & Revéret, L. (2022). Pose2Sim: An End-to-End Workflow for 3D Markerless Sports Kinematics—Part 2: Accuracy. *Sensors*, *22*(7), 2712. https://doi.org/10.3390/s22072712

Palermo, M., Lopes, J., André, J., Matias, A. C., Cerqueira, J., & Santos, C. P. (2022). A multi-camera and multimodal dataset for posture and gait analysis. *Scientific Data*, *9*(1). https://doi.org/10.1038/s41597-022-01722-7

Paravlić, A. H., Abazović, E., Milanović, Z., Vučković, G., Spudić, D., Hadžić, V., Pajek, M., & Vodičar, J. (2024). The association between unilateral and bilateral performance-related measures in elite female soccer players: a multifaceted investigation. *Frontiers in Physiology*, *15*. https://doi.org/10.3389/fphys.2024.1298159

Philipp, N. M., Čabarkapa, D., Cabarkapa, D. V., Eserhaut, D. A., & Fry, A. C. (2023). Inter-Device Reliability of a Three-Dimensional Markerless Motion Capture System Quantifying Elementary Movement Patterns in Humans. *Journal of Functional Morphology and Kinesiology*, *8*(2), 69. https://doi.org/10.3390/jfmk8020069

Philipp, N. M., Fry, A. C., Mosier, E. M., Čabarkapa, D., Nicoll, J. X., & Sontag, S. A. (2024). Biological reliability of a movement analysis assessment using a markerless motion capture system. *Frontiers in Sports and Active Living*, *6*. https://doi.org/10.3389/fspor.2024.1417965

Pineda-Espejel, H. A., Alarcón, E., Sánchez, R. M., Morales-Sánchez, V., & Gadea-Cavazos, E. (2021). Adaptive Social Factors and Precompetitive Anxiety in Elite Sport. *Frontiers in Psychology*, *12*. https://doi.org/10.3389/fpsyg.2021.651169

Pote, L., Proctor, S. P., McEwan, K., Davy, J., & Christie, C. J. (2019). The impact of a fast bowling spell on physiological, perceptual and performance responses in non-elite cricketers. *South African Journal of Sports Medicine*, *31*(1), 1. https://doi.org/10.17159/2078-516x/2019/v31i1a5624

Rawat, K., Błachnio, A., & Suppan, K. (2023). Psychometric Properties of the Polish Version of the Sports Anxiety Scale-2 (SAS-2). *International Journal of Environmental Research and Public Health*, *20*(14), 6429. https://doi.org/10.3390/ijerph20146429

Roggio, F., Trovato, B., Sortino, M., & Musumeci, G. (2024). A comprehensive analysis of the machine learning pose estimation models used in human movement and posture analyses: A narrative review [Review of *A comprehensive analysis of the machine learning pose estimation models used in human movement and posture analyses: A narrative review*]. *Heliyon*, *10*(21). Elsevier BV. https://doi.org/10.1016/j.heliyon.2024.e39977

Rossing, N. N., Christensen, A., & Skrubbeltrang, L. S. (2024). Coopetitive sport participation – an extreme case study among a diverse group of handball players with special needs. *Research Portal Denmark*. https://local.forskningsportal.dk/local/dki-cgi/ws/cris-link?src=ucn&id=ucn-517ffe2c-d6ec-4437-b63a-537c66cd49af&ti=Coopetitive%20sport%20participation%20%2013%20an%20extreme%20case%20study%20among%20a%20diverse%20group%20of%20handball%20players%20with%20special%20needs

Runswick, O. R., Roca, A., Williams, A. M., Bezodis, N. E., & North, J. S. (2017). The effects of anxiety and situation-specific context on perceptual–motor skill: a multi-level investigation. *Psychological Research*, *82*(4), 708. https://doi.org/10.1007/s00426-017-0856-8

Schaefer, A., Ferdinands, R. E. D., O'Dwyer, N., & Edwards, S. (2020). A biomechanical comparison of conventional classifications of bowling action-types in junior fast bowlers. *Journal of Sports Sciences*, *38*(10), 1085. https://doi.org/10.1080/02640414.2020.1741972

Schmid, M. J., Küttel, A., Charbonnet, B., Rivero, T., Schmid, J., Ronkainen, N. J., & Conzelmann, A. (2024). A Scoping Review on the Theoretical and Methodological Advances in the Study of Retirement From Elite Sport [Review of *A Scoping Review on the Theoretical and Methodological Advances in the Study of Retirement From Elite Sport*]. *Research Portal Denmark*. Technical University of Denmark. https://local.forskningsportal.dk/local/dki-cgi/ws/cris-link?src=sdu&id=sdu-27519d0a-a6eb-46dd-a5a0-

843b4ede86a9&ti=A%20Scoping%20Review%20on%20the%20Theoretical%20and%20Methodological%20Advances%20in%20the%20Study%20of%20Retirement%20From%20Elite%20Sport

Seiferheld, B. E., Frost, J., Østergaard, T. B., Krog, M., Klitgaard, K., & Zee, M. de. (2023). Full-Body Kinematics and Vertical Ground Reaction Forces in Elite Ten-Pin Bowling: A Field Study. *Sensors, 23*(19), 8284. https://doi.org/10.3390/s23198284

Senington, B., Lee, R. Y., & Williams, J. M. (2020). Biomechanical risk factors of lower back pain in cricket fast bowlers using inertial measurement units: a prospective and retrospective investigation. *BMJ Open Sport & Exercise Medicine, 6*(1). https://doi.org/10.1136/bmjsem-2020-000818

Siddiqui, H. U. R., Younas, F., Rustam, F., Flores, E. S., Ballester, J. B., Díez, I. de la T., Dudley, S., & Ashraf, I. (2023). Enhancing Cricket Performance Analysis with Human Pose Estimation and Machine Learning. *Sensors, 23*(15), 6839. https://doi.org/10.3390/s23156839

Slimani, M., Bragazzi, N. L., Znazen, H., Paravlić, A. H., Azaiez, F., & Tod, D. (2018). Psychosocial predictors and psychological prevention of soccer injuries: A systematic review and meta-analysis of the literature [Review of *Psychosocial predictors and psychological prevention of soccer injuries: A systematic review and meta-analysis of the literature*]. *Physical Therapy in Sport, 32*, 293. Elsevier BV. https://doi.org/10.1016/j.ptsp.2018.05.006

Taborri, J., Keogh, J., Kos, A., Santuz, A., Umek, A., Urbanczyk, C. A., Kruk, E. van der, & Rossi, S. (2020). Sport Biomechanics Applications Using Inertial, Force, and EMG Sensors: A Literature Overview [Review of *Sport Biomechanics Applications Using Inertial, Force, and EMG Sensors: A Literature Overview*]. *Applied Bionics and Biomechanics, 2020*, 1. Hindawi Publishing Corporation. https://doi.org/10.1155/2020/2041549

Tan, T., Gatti, A. A., Fan, B., Shea, K. G., Sherman, S. L., Uhlrich, S. D., Hicks, J. L., Delp, S. L., Shull, P. B., & Chaudhari, A. (2022). Towards Out-of-Lab Anterior Cruciate Ligament Injury Prevention and Rehabilitation Assessment: A Review of Portable Sensing Approaches [Review of *Towards Out-of-Lab Anterior Cruciate Ligament Injury Prevention and Rehabilitation Assessment: A Review of Portable Sensing Approaches*]. *medRxiv (Cold Spring Harbor Laboratory)*. Cold Spring Harbor Laboratory. https://doi.org/10.1101/2022.10.19.22281252

Trigt, B. van, Hogerwou, T. van, Leenen, T., Hoozemans, M. J. M., Helm, F. C. T. V. der, & Veeger, H. E. J. (2023). Magnitude and variability of individual elbow load in repetitive baseball pitching. *Scientific Reports, 13*(1). https://doi.org/10.1038/s41598-023-44333-x