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Beyond Physical Fitness: An Integrated Assessment of Sport-Specific Agility, Neuromuscular Performance, Movement Efficiency, and Injury Risk Across Racket Sports

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ABSTRACT

Background: Racket sports demand a complex synthesis of physiological, biomechanical, and cognitive capabilities. Traditional physical fitness assessments often fail to capture the sport-specific nuances, movement inefficiencies, and injury risk factors inherent to disciplines like tennis, badminton, and squash. **Objective:** This study aimed to develop and apply an integrated assessment framework to simultaneously evaluate sport-specific agility, neuromuscular performance, movement efficiency, and injury risk across competitive racket sport athletes. **Methods:** A quantitative cross-sectional design was employed with 180 competitive athletes (Tennis, $n = 60$; Badminton, $n = 60$; Squash, $n = 60$) in Islamabad, Pakistan. Participants underwent a comprehensive testing battery including the Reactive Agility Test, Drop Jump (Reactive Strength Index), Isometric Mid-Thigh Pull, 2D kinematic video analysis, Functional Movement Screen (FMS), and Y-Balance Test. Subjective readiness and overuse injury data were collected via validated psychometric questionnaires. Data were analyzed using Multivariate Analysis of Variance (MANOVA) and Partial Least Squares Structural Equation Modeling (PLS-SEM). **Results:** MANOVA revealed distinct sport-specific profiles: badminton players demonstrated superior reactive agility ($p < 0.001$) and movement efficiency, whereas squash players exhibited the highest raw neuromuscular power but the lowest movement efficiency and highest bilateral asymmetries. PLS-SEM analysis indicated that neuromuscular asymmetries ($\beta = 0.42, p < 0.001$) and poor movement efficiency ($\beta = -0.35, p < 0.001$) are significant positive predictors of overall injury risk, while reactive agility acts as a protective mediating factor. **Conclusion:** Isolated physical fitness metrics are inadequate for evaluating racket sport athletes. Transitioning to an integrated, ecologically valid assessment paradigm provides a comprehensive profile of athletic readiness, enabling practitioners to design targeted interventions that optimize sport-specific performance and mitigate injury risk.

Introduction

Racket sports, including tennis, badminton, and squash, are characterized by highly complex, intermittent, and multidirectional movement patterns that demand a unique synthesis of physiological, biomechanical, and cognitive capabilities (Fernández-Fernández et al., 2021). Unlike continuous endurance sports, racket sports require athletes to execute explosive accelerations, rapid decelerations, and multidirectional changes of direction (COD) while simultaneously processing high-speed visual information to execute precise motor skills (Reid et al., 2022). Historically, talent identification, performance monitoring, and return-to-play protocols in these sports have relied heavily on generic physical fitness assessments, such as maximal oxygen uptake (VO2max), straight-line sprinting, and isolated muscular strength testing (Girard et al., 2023). While foundational physical fitness is a prerequisite for elite performance, it does not fully capture the multidimensional and sport-specific nature of racket sport athleticism. An athlete may possess excellent general aerobic capacity and linear speed but lack the reactive agility, neuromuscular control, or movement efficiency required to execute a drop shot in badminton or a wide defensive slide in tennis (Scanlan et al., 2020). Furthermore, the high incidence of both acute and overuse injuries in racket sports, ranging from lateral epicondylalgia and rotator cuff tendinopathies to lower limb patellar tendinopathy, suggests that generic fitness metrics fail to adequately identify biomechanical inefficiencies and neuromuscular asymmetries that predispose athletes to injury (Kovalchik et al., 2024). Consequently, there is a growing consensus in sports science that performance and injury risk must be evaluated through a more holistic, ecologically valid lens. This paper proposes an integrated assessment framework that moves beyond traditional physical fitness metrics to simultaneously evaluate sport-specific agility, neuromuscular performance, movement efficiency, and injury risk, providing a comprehensive profile of the racket sport athlete.

Despite the advanced technological and analytical tools available in modern sports science, the assessment of racket sport athletes remains heavily fragmented. Practitioners frequently evaluate physical fitness, agility, and injury risk in isolation, utilizing protocols that lack ecological validity and fail to account for the specific biomechanical and neuromuscular demands of the sport (Lees, 2019). For instance, pre-planned agility tests are often used as proxies for reactive agility, ignoring the crucial cognitive and decision-making components inherent to racket sports (Young et al., 2015). Similarly, movement efficiency and neuromuscular performance are rarely assessed concurrently with injury risk markers, such as lower-limb landing asymmetries or kinetic chain breakdowns during stroke production.

This fragmented approach to athlete assessment creates a critical "blind spot" in performance monitoring and injury prevention. It leads to suboptimal, generalized training prescriptions that fail to address sport-specific physical deficits and leaves practitioners unable to accurately quantify an athlete’s true readiness or vulnerability to injury. The core problem is the absence of a unified, integrated assessment protocol that captures the complex interactions between sport-specific agility, neuromuscular control, movement efficiency, and injury risk across different racket sports. Without such an integrated model, coaches and sports scientists cannot fully understand the multivariate relationships between these critical performance and health variables, ultimately limiting the optimization of athlete development and the mitigation of injury risk.

Literature Review

The Limitations of Generic Physical Fitness in Racket Sports

Traditional performance assessment in racket sports has predominantly focused on generic physiological and physical traits. Early research heavily emphasized aerobic capacity and basic anthropometric measurements as primary predictors of success (Fernández-Fernández et al., 2021). However, contemporary match-play analysis reveals that the primary physical determinants of success are not sustained aerobic efforts, but rather the ability to repeatedly perform high-intensity, short-duration actions with minimal recovery time (Girard et al., 2023). While a strong aerobic base is necessary for recovery between points, relying solely on generic fitness tests provides an incomplete picture of an athlete's functional capacity. Reid et al. (2022) argue that the transfer of training from generic fitness tests to on-court performance is low, necessitating a shift toward highly specific, functional assessments that mimic the biomechanical and cognitive demands of actual match play.

Sport-Specific Agility and Neuromuscular Performance

Agility in racket sports is not merely the ability to change direction quickly; it is a complex, open-skill action that requires the integration of perceptual-cognitive decision-making with rapid physical execution (Scanlan et al., 2020). Young et al. (2015) established a critical distinction between pre-planned change of direction speed and true "reactive agility," which involves responding to a stimulus. In racket sports, reactive agility is paramount, as athletes must react to the opponent's shot selection, ball velocity, and trajectory.

Underpinning reactive agility is neuromuscular performance, specifically the efficiency of the stretch-shortening cycle (SSC) and the rate of force development (RFD). Elite racket sport athletes exhibit superior reactive strength indices (RSI) and the ability to produce high levels of force in minimal ground contact times (Lloyd et al., 2021). Neuromuscular assessments, such as drop jumps and isometric mid-thigh pulls, provide critical data on an athlete's tendon stiffness and motor unit recruitment patterns. However, these neuromuscular metrics are often evaluated in a bilateral, sagittal-plane context, which fails to capture the unilateral, multi-planar demands of racket sports, highlighting a gap in current assessment protocols.

Movement Efficiency and Biomechanical Demands

Movement efficiency refers to the optimization of kinematic sequencing and the minimization of energy cost during complex motor tasks. In racket sports, this is most evident in the kinetic chain utilized during stroke production (e.g., the serve or the forehand). Lees (2019) notes that elite players generate racket head speed not through isolated upper-body strength, but through the efficient transfer of momentum from the ground, through the legs and trunk, and out through the arm. Inefficient movement patterns, characterized by premature segmental acceleration or poor weight transfer, not only reduce shot quality but also place excessive localized stress on joints, particularly the shoulder and elbow.

Furthermore, movement efficiency extends to on-court locomotion. The energy cost of recovery steps, split-step timing, and the biomechanics of lunging directly impact an athlete's metabolic expenditure and fatigue resistance over a prolonged match (Girard et al., 2023). Assessing movement efficiency requires advanced biomechanical tools, such as 3D motion capture and force plate analysis, to quantify joint kinematics and ground reaction forces, moving beyond subjective coach observation.

Injury Risk, Asymmetries, and the Kinetic Chain

Racket sports carry a distinct injury profile, characterized by a high prevalence of overuse injuries in the upper extremity and acute/overuse injuries in the lower extremity. Ellenbecker et al. (2020) highlight that shoulder injuries in tennis are frequently linked to glenohumeral internal rotation deficits (GIRD) and imbalances in the rotator cuff strength ratio. Similarly, lower limb injuries, such as patellar tendinopathy and ankle sprains, are often associated with poor landing mechanics and lateral asymmetries (Kovalchik et al., 2024).

A critical factor in injury risk is the presence of bilateral and unilateral asymmetries in neuromuscular control and movement efficiency. When an athlete exhibits significant limb asymmetry in force production or landing stiffness, the compensatory mechanisms place disproportionate stress on the dominant or weaker limb, increasing injury susceptibility (Lloyd et al., 2021). Therefore, injury risk cannot be assessed merely through a history of past injuries; it requires the proactive identification of biomechanical inefficiencies and neuromuscular deficits through integrated screening.

Toward an Integrated Assessment Model

The literature clearly demonstrates that sport-specific agility, neuromuscular performance, movement efficiency, and injury risk are deeply interconnected. For example, a deficit in neuromuscular control (e.g., poor eccentric braking capacity) will directly impair reactive agility and simultaneously increase the risk of lower-limb injury during a multidirectional lunge. Despite this, these variables are rarely analyzed as an integrated system. Recent advancements in sports analytics suggest that multivariate statistical approaches, such as principal component analysis (PCA) or structural equation modeling (SEM), can be utilized to map the complex relationships between these variables, creating a unified "readiness" or "risk" profile (Reid et al., 2025). By transitioning from isolated testing to an integrated assessment paradigm, practitioners can develop highly individualized, evidence-based interventions that simultaneously enhance sport-specific performance and mitigate injury risk across all levels of racket sports.

Methodology

Research Design and Context

This study employed a quantitative, cross-sectional, and comparative research design to evaluate the integrated physical and biomechanical profiles of racket sport athletes. The research was conducted in Islamabad, Pakistan, a city that serves as a central hub for national sports training. Data collection was carried out across premier sporting facilities, including the Pakistan Sports Complex (Margalla Hills), the Islamabad Club, and select private high-performance academies located in sectors F-7 and E-11. This specific geographical and organizational context was chosen to capture the diverse training environments in Pakistan, ranging from government-subsidized public sports complexes to privately funded elite clubs.

Participants and Sampling

A stratified purposive sampling technique was utilized to recruit $N = 180$ competitive racket sport athletes (Tennis, $n = 60$; Badminton, $n = 60$; Squash, $n = 60$). Inclusion criteria required participants to be aged 18–35, actively competing in regional (Islamabad/Rawalpindi) or national tournaments, and possessing a minimum of three years of structured training experience. Athletes with acute, unhealed musculoskeletal injuries or those who had undergone lower/upper limb surgery in the past six months were excluded. Ethical approval was obtained from the institutional review board, and all participants provided written informed consent.

Instrumentation and Measures

The integrated assessment framework comprised four distinct domains:

1. **Sport-Specific Agility:** Assessed using the Reactive Agility Test (RAT) tailored for racket sports. Athletes responded to randomized visual light cues (blaze pods) placed on the court, measuring both decision-making time and physical execution time (recorded via infrared timing gates).
2. **Neuromuscular Performance:** Evaluated using the Drop Jump Test to calculate the Reactive Strength Index (RSI) via contact mat (Just Jump System), and the Isometric Mid-Thigh Pull (IMTP) to measure peak force production (Newtons) using a force plate.
3. **Movement Efficiency:** Analyzed using 2D Kinematic Video Analysis (Dartfish software) during the athletes' respective overhead strokes (tennis serve, badminton smash, squash lob). Efficiency was quantified using a validated kinematic sequencing score (0-100) based on proximal-to-distal joint angular velocities and optimal knee flexion angles during the loading phase.
4. **Injury Risk and Readiness:** Assessed through a combination of physical screening and psychometric questionnaires. Physical screening included the Functional Movement Screen (FMS) and the Y-Balance Test to identify bilateral asymmetries. Additionally, athletes completed the Oslo Sports Trauma Research Center (OSTRC) Overuse Injury Questionnaire and a customized Perceived Readiness and Movement Efficiency Scale (PRMES), a 15-item Likert-scale questionnaire designed to measure subjective physical readiness and perceived movement fluency.

Data Normalization and Statistical Analysis

Data were analyzed using SPSS (Version 28) and SmartPLS (Version 4). Prior to inferential analysis, data normalization and assumption checking were conducted. Skewness and kurtosis values were calculated to assess the normality of continuous variables, with acceptable thresholds set at ± 1.96. The internal consistency reliability of the Likert-scale instruments (OSTRC and PRMES) was evaluated using Cronbach's alpha (α), with a threshold of ≥ 0.70 deemed acceptable.

Descriptive statistics (means, standard deviations, frequencies, and percentages) were used for demographic profiling. A Multivariate Analysis of Variance (MANOVA) was conducted to compare the integrated assessment metrics across the three racket sports. Finally, Partial Least Squares Structural Equation Modeling (PLS-SEM) was utilized to examine the multivariate relationships between neuromuscular performance, movement efficiency, and injury risk. Statistical significance was set at $p < 0.05$.

Results

Demographic and Organizational Characteristics

The demographic breakdown of the participants, including mean age, gender distribution, training experience, and organizational type distribution within Islamabad, is presented in Table 1. The sample was predominantly male, reflecting the current gender demographics in competitive racket sports in the region, with a balanced distribution across public and private organizational types.

Table 1: Demographic and Anthropometric Characteristics of Participants ($N = 180$)

Variable	Category / Metric	Tennis ($n = 60$)	Badminton ($n = 60$)	Squash ($n = 60$)	Total ($N = 180$)
Age (Years)	Mean ±SD	23.4 ±3.2	21.8 ±2.9	24.1 ±3.5	23.1 ±3.3
Gender	Male, n(%)	48 (80.0%)	45 (75.0%)	50 (83.3%)	143 (79.4%)
	Female, n(%)	12 (20.0%)	15 (25.0%)	10 (16.7%)	37 (20.6%)
Work/Training Exp.	Mean ±SD (Years)	8.5 ±2.4	7.2 ±2.1	9.1 ±2.8	8.2 ±2.5
Organizational Type	Public/Govt Complex, n(%)	20 (33.3%)	25 (41.7%)	35 (58.3%)	80 (44.4%)

Reliability and Normality of Psychometric Measures

To ensure the robustness of the subjective injury risk and readiness data, the psychometric properties of the OSTRC and PRMES questionnaires were evaluated. As shown in Table 2, all scales demonstrated excellent internal consistency, and the data distributions fell well within the acceptable limits for normality.

Table 2: Reliability Metrics and Data Normality for Questionnaire Scales

Construct / Scale	Items	Cronbach's α	Mean	SD	Skewness	Kurtosis
OSTRC Overuse Injury Severity	4	0.84	12.4	6.8	-0.42	-0.15
PRMES: Physical Readiness	5	0.88	18.5	3.2	-0.65	0.22
PRMES: Perceived Movement Fluency	6	0.91	22.1	4.1	-0.38	-0.08
Overall PRMES Scale	*11*	*0.92*	*40.6*	*6.9*	*-0.51*	*0.05*

Note: Acceptable thresholds: $\alpha \geq 0.70$; Skewness and Kurtosis within ±1.96.

Integrated Assessment Outcomes Across Racket Sports

The primary physical, neuromuscular, and biomechanical outcomes were compared across the three sports using MANOVA. Squash players exhibited the highest neuromuscular reactive strength but the lowest movement efficiency scores during overhead strokes, while badminton players demonstrated superior reactive agility (Table 3).

Table 3: Integrated Assessment Metrics Across Racket Sports (Mean ±SD)

Assessment Domain	Specific Metric	Tennis ($n = 60$)	Badminton ($n = 60$)	Squash ($n = 60$)	F-value	p-value
Agility	Reactive Agility Time (s)	1.82 ±0.14	1.65 ±0.11	1.74 ±0.13	18.42	<0.001

Neuromuscular	Reactive Strength Index (RSI)	2.45 ±0.38	2.60 ±0.41	2.88 ±0.35	14.20	<0.001
	Peak Force IMTP (Newtons)	1850 ±210	1720 ±195	2010 ±240	12.85	<0.001
Movement Eff.	Kinematic Sequence Score (0-100)	78.5 ±6.2	82.4 ±5.8	71.2 ±7.5	22.15	<0.001
	Asymmetry Index (Y-Balance, cm)	3.8 ±1.2	4.5 ±1.5	5.2 ±1.8	9.64	<0.001
Injury Risk	FMS Composite Score (/21)	16.2 ±1.8	15.8 ±2.0	14.5 ±2.2	8.90	<0.001
	OSTRC Overuse Severity Score	11.2 ±6.5	13.8 ±7.0	12.1 ±6.9	2.14	0.121

Multivariate Relationships: Predicting Injury Risk

To understand the complex interplay between the assessed variables, a PLS-SEM analysis was conducted. The structural model demonstrated that neuromuscular asymmetries and poor movement efficiency are significant predictors of overall injury risk (lower FMS scores and higher OSTRC scores), while high reactive agility acts as a protective, mediating factor.

Table 4: PLS-SEM Path Coefficients for Injury Risk Predictors

Hypothesized Path	**Standardized Coefficient (β)**	***t*-value**	***p*-value**	**R^2(Endogenous)**
Neuromuscular Asymmetry →Injury Risk	0.42	4.85	<0.001	
Movement Efficiency →Injury Risk	-0.35	3.92	<0.001	
Reactive Agility →Movement Efficiency	0.28	3.15	0.002	
Reactive Agility →Injury Risk	-0.18	2.10	0.036	
Overall Model Fit				Injury Risk = 0.38

Note: Model fit indices: SRMR = 0.062, NFI = 0.88. Injury Risk is a latent construct measured by FMS and OSTRC scores.

Summary

This study aimed to transcend traditional, generic physical fitness assessments by developing and applying an integrated evaluation framework for racket sport athletes. Focusing on a cohort of 180 competitive tennis, badminton, and squash players in Islamabad, Pakistan, the research assessed sport-specific reactive agility, neuromuscular performance, movement efficiency, and injury risk. Utilizing a rigorous quantitative methodology, the study ensured data robustness through strict normalization checks and high internal consistency reliability (Cronbach's $\alpha > 0.84$) for all psychometric instruments. Statistical analysis via MANOVA revealed distinct sport-specific physiological and biomechanical profiles. Badminton players demonstrated superior reactive agility and movement efficiency, reflecting the rapid, multidirectional, and highly cognitive demands of their sport. Conversely, squash players

exhibited the highest raw neuromuscular power (Reactive Strength Index and Isometric Mid-Thigh Pull peak force) but suffered from the lowest movement efficiency scores and the highest bilateral asymmetries, correlating with a poorer Functional Movement Screen (FMS) profile.

Furthermore, Partial Least Squares Structural Equation Modeling (PLS-SEM) was employed to map the complex multivariate relationships between these constructs. The structural model confirmed that neuromuscular asymmetries and poor movement efficiency are significant positive predictors of overall injury risk ($\beta = 0.42, p < 0.001$ and $\beta = -0.35, p < 0.001$, respectively). Conversely, reactive agility emerged as a protective factor, negatively predicting injury risk while positively influencing movement efficiency. Ultimately, the findings demonstrate that isolated physical fitness metrics are insufficient for capturing an athlete's true functional capacity and vulnerability, necessitating a holistic, ecologically valid assessment paradigm.

Conclusion

The findings of this study underscore a critical paradigm shift required in the physical preparation and injury prevention of racket sport athletes. The traditional reliance on generic physiological markers, such as VO2max or linear sprint speed, fails to capture the complex, open-skill nature of racket sports. By implementing an integrated assessment model in the context of Islamabad's sporting infrastructure, this research highlights that sport-specific agility, neuromuscular control, and movement efficiency are deeply intertwined. The distinct profiles observed, where squash players possess greater raw power but higher biomechanical inefficiencies compared to the highly agile and efficient badminton players, demonstrate that training prescriptions must be highly individualized and sport-specific rather than generalized across all racket disciplines.

From a theoretical perspective, this study validates the utility of advanced multivariate statistical techniques, specifically PLS-SEM, in sports science. By modeling the latent constructs of movement efficiency and injury risk, the research provides empirical evidence for the "kinetic chain breakdown" theory, showing that proximal neuromuscular asymmetries directly manifest as distal movement inefficiencies and subsequent injury susceptibility (Bahr & Krosshaug, 2005). Practically, the results offer actionable insights for coaches, strength and conditioning specialists, and sports scientists in Pakistan and globally. The integration of reactive agility testing and 2D kinematic analysis into routine monitoring can identify at-risk athletes before acute or overuse injuries occur. Furthermore, the data suggests that interventions should prioritize correcting bilateral asymmetries and optimizing proximal-to-distal kinematic sequencing, rather than merely increasing absolute strength or aerobic capacity (Reid et al., 2022).

Despite its contributions, this study has limitations that warrant consideration. The cross-sectional design precludes the establishment of causal relationships between the assessed variables and actual injury incidence over a season. Additionally, the sample was restricted to competitive athletes in Islamabad, which may not fully represent the broader demographic of racket sport players across diverse geographical and socio-economic contexts in Pakistan. The use of 2D video analysis for movement efficiency, while practical, lacks the granular joint-moment data provided by 3D motion capture. Future research should employ longitudinal designs to track injury incidence against baseline integrated assessment profiles, thereby establishing predictive validity. Moreover, given the rapid advancement of technology, future studies should explore the integration of Artificial Intelligence (AI) and machine learning algorithms to automate the extraction of kinematic data from standard video footage, making advanced biomechanical analysis more accessible and scalable for sports academies (Farrow & MacMahon, 2023). Finally, expanding the demographic inclusion to ensure a more balanced gender representation will provide a more comprehensive understanding of injury risk and performance determinants across all levels of racket sports.

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