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Kinetic and Kinematic Correlates of Peak (vertical) Ground Reaction Force and Knee Valgus During Jump Smash Landing in Male Badminton Players

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Abstract
Introduction: The jump smash in badminton generates considerable mechanical loading on the lower limbs, particularly during take-off and landing phases. Excessive frontal-plane knee mechanics, such as dynamic knee valgus, have been associated with increased anterior cruciate ligament (ACL) and patellofemoral injury risk. The present study investigated the relationship between peak vertical ground reaction forces (GRF) during take-off and landing and knee valgus angles in male badminton athletes.
Methodology: Ten state-level players aged 18-25 years performed three standardized jump smash trials, with the best trial analysed. Peak take-off GRF (ptGRF), peak landing GRF (plGRF), and knee valgus angles were collected using a Kistler force plate and 2-D motion capture.
Results: Pearson correlation analysis showed a moderate negative correlation between ptGRF and take-off knee valgus ($r = -0.50$, $p \approx 0.05$), and a moderate positive correlation between plGRF and landing knee valgus ($r = 0.60$, $p \approx 0.05$).
Conclusion: These findings indicate that knee valgus mechanics interact differently with GRF depending on the movement phase. Strengthening trunk and hip neuromuscular control strategies may improve both performance and injury resilience in badminton athletes.

Keywords: Badminton Jump smash, Ground reaction force, Knee valgus, Biomechanics, ACL injury risk, Landing mechanics

Introduction
Among its methods, the jump smash is one of the strongest and most critical strokes, typically carried out with high vertical and horizontal forces to achieve maximum shuttle speed (Hung *et al*., 2020) [13]. Nevertheless, the violent take-off and single-leg or unilateral landing patterns of badminton jump smashes subject athletes to significant mechanical loading on hip, knee, and ankle joints (Rambely *et al*., 2005) [28]. Badminton is a power, multi-planar sport that involves repeated jumping, quick decelerations and single leg landings; the jump smash places high external loads on the lower extremity and is involved in non-contact knee injuries (Cohen *et al*., 2015; Hung *et al*., 2020) [8, 3]. When landing, ground reaction force (GRF) is an important variable because it indicates the amount of external load transmitted across the musculoskeletal system (Niu *et al*., 2014) [26].
High peak GRFs have been linked to excessive joint stresses and are a risk factor for lower-limb injury (Bates *et al*., 2013) [3]. Altered frontal-plane knee mechanics, like dynamic knee valgus, have specifically been implicated in anterior cruciate ligament (ACL) injuries and patellofemoral dysfunctions (Herrington & Munro, 2010; Hewett *et al*., 2005) [10, 11]. For badminton, jump smash landing mechanics have been associated with higher knee valgus moments, especially on the non-racquet side or during unexpected movements (Kimura *et al*., 2012; Tseng *et al*., 2021) [17, 36]. Although earlier research in volleyball and soccer demonstrated high correlations between GRF and knee valgus angle or moment (Zahradnik *et al*., 2014; Claudino *et al*., 2017) [39, 6], current evidence in badminton is scarce.

Types of Badminton Strokes
Badminton consists of a variety of strokes done with forehand or backhand technique. The five

basic strokes are:

1. **Serve:** Begins play, long and high in singles, or short and low in doubles.
2. **Clear: A** defensive shot, hitting the shuttle high and deep into the other court, done underhand or overhand.
3. **Smash:** An attack, downward shot, similar to a volleyball spike, used to gain points.
4. **Drive:** A quick, flat shot taken at shoulder height, making players react hastily.
5. **Drop Shot:** A gentle stroke making the shuttle drop barely over the net into the opponent's front court.

These shots are employed tactically to manoeuvre rallies, put pressure on, and take advantage of weaknesses of opponents. (Cohen *et al*., 2025; Grice, T. 2008; Kwan, M.Y *et al*., 2010; Subramaniam, V *et al*., 2015; Waddell, K 2014) [8, 9, 20, 32, 37].

Ground reaction forces (GRF) measure the external load transferred from the playing surface to the body and are typically resolved into three orthogonal components: vertical (V-GRF), anterior-posterior (AP-GRF) and medial-lateral (ML-GRF). The peak vertical GRF (ptGRF) is a measure of impact magnitude (how "hard" one lands), while AP and ML components represent forward/backward braking and medial/lateral shear that may generate frontal-plane moments at the knee (Niu *et al*., 2014) [26].

Mechanically, there are two peak-GRF moments during a jump-smash cycle — the peak take-off (ptGRF), when one explosively propels upward, and the peak landing (plGRF), when one is absorbing impact.

Peak take-off forces represent propulsive requirements and eccentric-concentric muscle activity preloading tissues, and those at landing represent impact absorption and the external load transmitted by the knee. Greater and faster applied ptGRFs, and shorter stance durations, increase joint loading rates and neuromuscular control requirements are highly correlated with augmented knee injury risk (Bates *et al*., 2013) [3].

Knee valgus (dynamic medial collapse of the knee—abduction/medial displacement of the tibiofemoral joint in the frontal plane) is an important kinematic marker associated with increased ACL strain and other knee disorders.

Future research has demonstrated that athletes who eventually experienced ACL rupture exhibited larger knee abduction angles and moments upon landing tasks; injured competitors experienced ~2.5× larger knee abduction moment and ≈20% larger GRF at landing than their uninjured counterparts. Knee abduction moment could predict ACL injury with ~78% sensitivity and ~73% specificity, identifying valgus loading as a strong risk factor (Hewett *et al*., 2005) [11]. Normative dynamic valgus angles are task- and sex-dependent. As an illustration, for drop-jump and single-leg step-landing tasks, normative knee valgus ranges of about 3-8° in males and 7-13° in females have been reported (Herrington & Munro, 2010) [10]. For unilateral step landing the ranges change to about 1-9° (males) and 5-12° (females). Values well above these ranges (or sudden spikes upon landing) have been related to increased risk of ACL and patellofemoral injuries.

Badminton jump smash has been described as one of the most effective and conclusive attacking movements in the game, usually deciding rallies by its rapid speed, sharp angle, and accuracy (Cohen *et al*., 2015; Hung *et al*., 2020) [8, 13].

It is used extensively by top players to win points or create poor returns; performance studies of international games have indicated that smashes are responsible for over 53.9% of victorious strokes in men's singles contest (Abdullahi & Coetzee, 2017) [1] (Tsai & Chang, 1998; Tong & Hong, 2000; Rambely *et al*., 2005) [34, 33, 28]. Among these, the jump smash—executed in mid-air—produces the highest shuttlecock speeds, averaging 93-97 m/s, and requires superior timing, power generation, and body control (Kwan *et al*., 2010; Abián *et al*., 2014) [20, 2]. From a biomechanical perspective, jump smash is a multi-phase, whole-body movement with both upper- and lower-extremity coordination to effectively transfer kinetic energy from the ground, through the body, to the shuttle and racket (Tsai & Chang, 2018; Rambely *et al*., 2005) [35, 28]. The motion is described in five major phases:

1. **Preparation Phase:** The player aligns with a split step or scissor stance to maximize balance and preparation (Kwan *et al*., 2010) [20]. Appropriate trunk rotation and shoulder alignment are achieved, laying the foundation for explosive action.
2. **Backswing Phase:** The racket arm recedes while the non-racket arm raises for balance. Shoulder and trunk muscles store elastic energy through the stretch-shortening mechanism (Tsai & Chang, 2018) [35].
3. **Take-Off Phase:** An explosive lengthening at the hip, knee, and ankle produces upward and forward thrust. Through this phase, maximum take-off ground reaction force (ptGRF) is generated, which indicates the propulsive ability of the athlete (Rambely *et al*., 2005) [28].
4. **Mid-Air Swing/Smash Phase:** In flight, the trunk twists and the racket arm hasten towards shuttle contact. The kinetic chain channels energy progressively from lower limbs to trunk, shoulder, elbow, and wrist (Kwan *et al*., 2010; Tsai & Chang, 2018) [20, 35].
5. **Landing Phase:** Post-shuttle impact, players usually land on one leg (commonly the non-racket leg), translating massive ground reaction forces (plGRF) and body momentum decelerations. It is the most susceptible to injury phase; studies suggest that neuromuscular control at landing could be poor and potentially cause knee valgus collapse and ACL loading (Kimura *et al*., 2012; Tseng *et al*., 2021) [17, 36].

   Biomechanical experiments have substantiated that the landing phase of the jump smash elicits vertical GRFs of 3-4 times body weight (Kimura *et al*., 2012; Tseng *et al*., 2021) [17, 36], along with high medial-lateral forces testing knee stability (Hung *et al*., 2020) [17, 13]. Additionally, expert players demonstrate controlled knee flexion and trunk inclination upon landing, measures also linked to decreased valgus angles and more secure energy absorption (Kimura *et al*., 2012) [17].

Methodology

In the present study, the primary objective was to examine the relationship between peak ground reaction forces (during take-off and landing) and knee valgus among badminton players, given the association of knee valgus with lower limb injuries, particularly anterior cruciate ligament (ACL) injuries, which are common in sports involving frequent jumps and rapid directional changes. Ten male athletes, aged 18-25 years, actively participating in competitive university and regional badminton events and free from any prior lower limb injuries, were recruited using a simple random sampling technique to ensure equal probability of selection, reduce sampling bias, and enhance data representativeness.

Based on a literature review and measurement feasibility, two independent variables—peak take-off ground reaction force (ptGRF) and peak landing ground reaction force (plGRF)—and one dependent variable, knee valgus angle, defined as the medial deviation of the knee relative to the hip and ankle during landing, were selected.

Table 1: Variable with units

Sl. No	Parameters	Unit
1.	Peak Ground Reaction Force (ptGRF) Take-off phase	Newton (N)
2.	Peak Landing Reaction Force (plGRF) Landing phase	Newton (N)
3.	Knee valgus angle	Degrees (°)

A correlational research design was employed to observe natural variations in these biomechanical variables without experimental manipulation. Data collection involved using a Basler Ace 2-D camera with reflective markers on anatomical landmarks to capture knee valgus angles during jump-landing tasks, while vertical ground reaction forces were recorded simultaneously using a KISTLER force plate (9287CA series) and analysed with BIOWARE software to extract peak values. Participants performed three standardized jump-landing trials for assessment.

Statistical analyses were conducted using SPSS Version 22, including descriptive statistics (mean ± standard deviation), Pearson Product Moment Correlation to quantify the relationships between ptGRF, plGRF, and knee valgus angles, and t-tests to evaluate statistical significance, with significance set at $p < 0.05$.

Procedure: Each participant performed a jump smash in front of the mounted 2-D cameras, which were fixed on tripods at a height of 1.50 metres from the ground. Cameras were positioned to capture motion in both the sagittal and frontal planes, placed at a minimum distance of 5 metres adjacent to the side of the badminton court and perpendicular to the plane of motion. A standard reference frame (1 × 1 × 1 m) was placed at the centre of the court, at least 1 metre away from the participant, to facilitate calibration of the video data. The cameras were carefully angled and panned to accurately capture the deflection and movement of the knee joint during the jump smash. Reflective markers were placed on key anatomical landmarks, including the anterior superior iliac spine (ASIS), the centre of the base of the patella, and the tibial tuberosity, to enable precise kinematic analysis. Each participant performed three trials of the jump smash to ensure reliability and consistency of the measurements, with the mean values of the trials used for subsequent analysis.

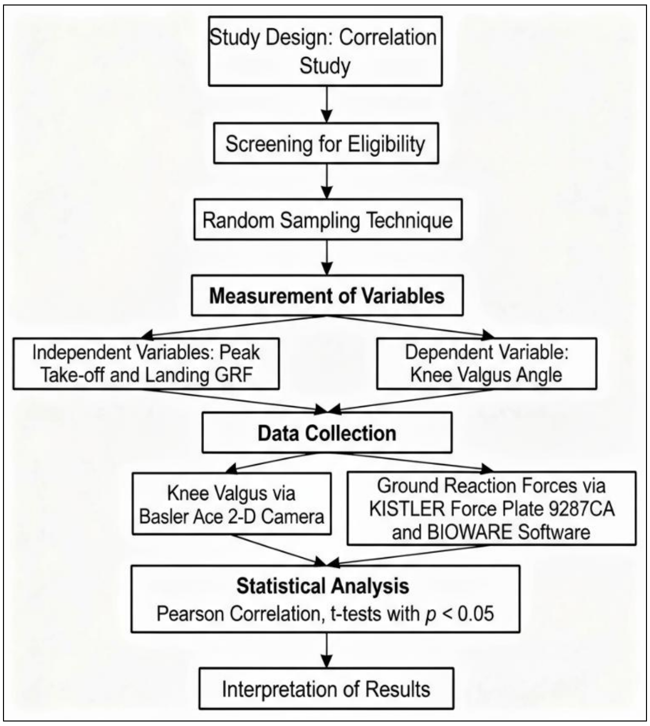

Fig 1: Flowchart of the study

Results

A total of 30 subjects were analysed for lower-limb kinetic and kinematic parameters, including Ground reaction force (take off & landing) and knee valgus angle during both landing and take-off phases.

Descriptive Statistics

Table 2: Descriptive Statistics

Variables	Mean	SD	Minimum	Maximum
PtGRF (Take-off Peak Force, N)	1450.1 N	± 107.3 N	1290 N	1680 N
PlGRF (Landing Peak Force, N)	2655.7 N	± 192.7 N	2342 N	2978 N
Knee Valgus (Landing, °)	15.10°	± 1.72	11.3°	17.0°
Knee Valgus (Take-off, °)	14.97°	± 1.98	11.4°	17.0°

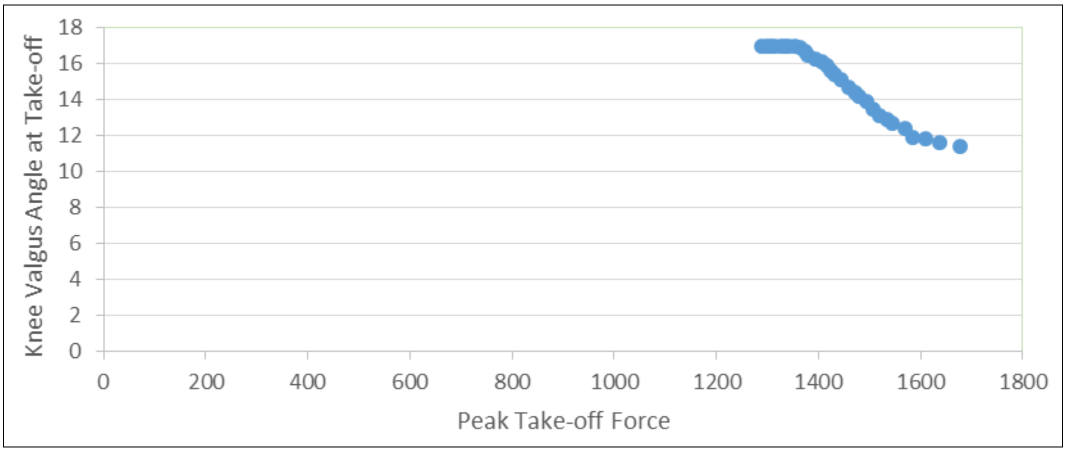

Fig 2: Peak Take-off Ground Reaction Force vs Knee valgus angle

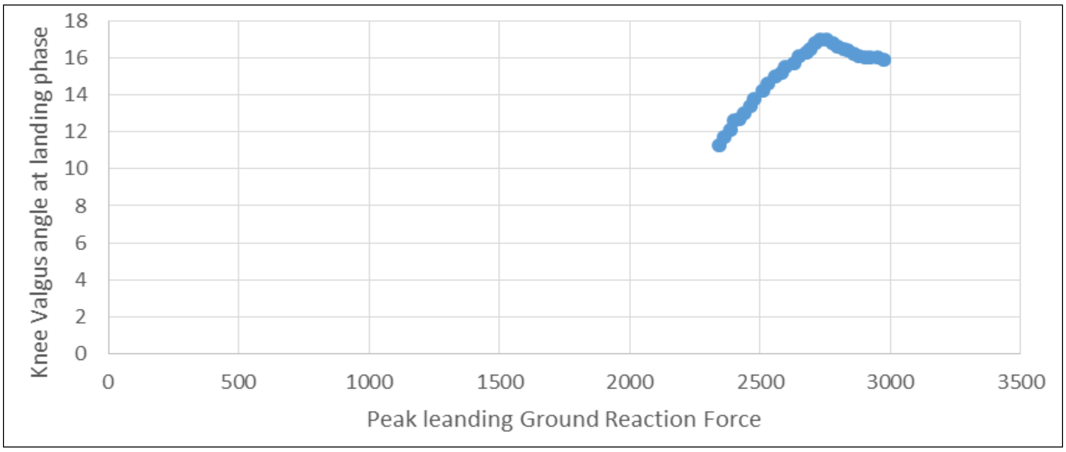

Fig 3: Peak Landing Ground Reaction Force vs Knee valgus angle

Descriptive Statistics Interpretation

- Take-off Peak Force (vGrf): Greater deviation in vertical propulsion power (SD ≈ ± 107.3 N) suggests uneven lower-limb impulse generation, consistent with the negative correlation trend observed with take-off knee valgus.
- Landing Peak Force (PlGRF): Moderate variability is noted (SD ≈ ± 192.7 N), indicating consistent landing performance across participants despite slight individual differences.
- Valgus Angles: Landing valgus angles show a relatively narrow spread (11°-17°), which aligns with healthy biomechanical limits; take off valgus angles stay similar but less tightly clustered.

Correlations Statistics

Table 3: Correlations values between the variables

Relationship	R-Value	Direction	P-value
ptGRF vs Take-off Knee Valgus	−0.50	Moderate Negative	≈ 0.05
PlGRF vs Landing Knee Valgus	+0.60	Moderate Positive	≈ 0.05

Correlations Statistics Interpretation

- Negative correlation $r \approx -0.5$ for peak takeoff force (vGrf) vs takeoff knee valgus angle (≤18° max), with statistical significance $p = 0.05$.
- Positive correlation $r \approx +0.6$ for landing peak force (PlGRF) vs landing knee valgus angle (≤17° max), with statistical significance $p = 0.05$.
- Take-off Phase (Negative Correlation): Higher knee valgus angle is associated with reduced take off peak force, linked to reduced hip and trunk stability, suggesting weak gluteal and core co-activation.
- **Landing Phase (Positive Correlation):** Higher knee valgus correlates with greater landing peak force, meaning greater valgus angles absorb or produce higher impact forces — a potential injury mechanism.
- These findings support prior research showing associations between dynamic valgus and abnormal loading in jump-land tasks.

Discussion

Badminton-task-specific research suggests that single-leg landings from overhead strokes or lateral smash tasks tend to generate greater knee valgus alignment and valgus moments than other types of landing contexts, with backhand-side or unexpected landings showing especially high levels of valgus demands (Kimura *et al.*, 2012; Tseng *et al.*, 2021) [17, 36]. Also, sexual differences have been noted: female badminton players typically have greater valgus angles (and changed hip/ankle mechanics) while male players at times have greater valgus moments, emphasizing that angle and moment are similar but different constructs.

While most research correlates components of GRF (magnitude, direction, rate) with increased frontal-plane knee load, the correlation between peak GRF alone (take-off or landing) and knee valgus angle is not necessarily consistent. Several factors mediate whether a given GRF produces valgus collapse. Vector direction of the resultant GRF (ML and AP components), trunk position, hip/ankle strength and control, foot placement, landing strategy (anticipated vs unanticipated), and whether analyses use angle (2D) versus moment (3D kinetics). Therefore, while high GRF (particularly when combined with lateral/AP shear and brief time-to-peak) raises the mechanical demand that can create valgus, peak GRF alone would not reliably be able to predict valgus angle without considering concurrent kinematics and kinetics.

For badminton clinicians and coaches, the assessment of ptGRF and plGRF alongside GRF vector components and frontal-plane knee kinetics (abduction moment) — along with trunk and hip control parameters — provides a more comprehensive evaluation of valgus risk than peak GRF in isolation. Training interventions that minimize landing forces, delay time-to-peak, and enhance trunk/hip neuromuscular control (eccentric control, hip abductor/external rotator strength, and proprioception) are cited by the literature for the mitigation of dynamic valgus and ACL risk.

Biomechanical and Risk of Injury

There is a negative linear correlation between take off knee valgus angle and peak take off force: with increasing knee valgus, the peak force during take-off reduces significantly. This indicates that greater valgus during take-off relates to worse force output, which could be associated with

Decreased hip and trunk control: Decreased or delayed hip and trunk control may allow for increased femoral adduction and internal rotation, creating more dynamic knee valgus during landing and thus increasing lateral limb loading. Several biomechanical reviews and investigations have associated dysfunctional hip/pelvic control with increased dynamic knee valgus and high knee abduction moments, both of which are associated with noncontact knee injury mechanisms. These proximal deficits can thus account for the apparent relationship between plGRF and knee valgus.

Inefficient kinetic chain activation: The kinetic chain (trunk → hip → knee → ankle) needs to be activated eccentrically on landing and concentrically on propulsion. The high negative correlation between VGRF and knee valgus in our data implies that when vertical propulsive force is decreased (or redistributed), frontal-plane control is lost — a probable indication of inadequate kinetic-chain activation or suboptimal muscle-activity sequencing. Intervention studies show neuromuscular training that aims at hip and trunk control to enhance landing biomechanics and minimize valgus measures. Imbalanced muscle function: Dynamic valgus is characterized by underuse of the lateral/posterior kinetic chain (gluteal, hamstrings), or overuse/compensation by medial (adductors, quadriceps) musculature, inhibiting efficient power transfer.

Imbalanced hip abductor/extensor to knee stabilizer recruitment: (e.g., relatively weak gluteus Medius or delayed vastus medialis activation) results in a frontal-plane collapse at the knee. This instability can enhance lateral loading and alter force vectors, in accord with high plGRF / high valgus pattern found. Research of neuromuscular programs (plyometric + balance + trunk/hip strengthening) demonstrates decreases in dynamic valgus and increases in muscular co-activation and control of landing. Landing injury risk: Positive relationship between plGRF and landing valgus indicates increased tissue strain at higher forces, requiring screening and corrective exercise as a priority.

These results underscore the biomechanical and neuromuscular significance of neutral knee position during lower-limb explosive actions. High take-off knee valgus is associated with lower force production, which can decrease performance and enhance susceptibility to injury by virtue of aberrant load management in the lower-extremity kinetic chain. Specifically targeted interventions to enhance trunk and hip stability and neuromuscular control may decrease dynamic valgus and enhance force production

The moderate positive relationship between knee valgus angle and landing peak force indicates that higher ground reaction forces produced by athletes during landing are also associated with increased medial knee deviation (valgus) at the peak force point. This is consistent with literature that shows greater valgus at increased landing loads could increase joint stresses, which might be a factor in the risk of injury such as ACL injury, particularly in repetitive jump-landing manoeuvre sports.

These results underscore the need to screen and train both landing mechanics and strength, with a specific emphasis on neuromuscular control to restrict excessive knee valgus under load to minimize risk of injury.

The landing is biomechanically stressful, as it is the process of absorbing the high impact forces of the jump. This is where risk of knee injury is highest.

General Association (Risk of Injury): Throughout sports biomechanics literature, augmented ground reaction force (GRF) upon landing is an identified contributing risk factor for inordinate valgus loading, which in turn elevates stress in the anterior cruciate ligament (ACL). Knee valgus is generally accepted as the chief mechanism for non-contact ACL injuries.

Smash-Specific Load: Scientific studies have confirmed a direct correlation by comparing various badminton stroke conditions. Landings conducted under the active smash condition yielded not only greater vertical ground reaction force, but also greater knee valgus angles at initial ground contact, in comparison to target striking or shadow practice conditions. This verifies that the smash landing's high-force environment is directly linked with greater knee valgus stress.

Table 4: Phase-Specific Biomechanical Relationships Between Ground Reaction Force and Dynamic Knee Valgus

Phase	Biomechanical Perspective	GRF Implication	Knee Valgus Implication	Muscular / Neuromuscular Link	Performance & Injury Outcome
Take-off	Body generates propulsive force to jump	High propulsive GRF → Force should transfer efficiently through kinetic chain	Valgus indicates poor alignment → inefficient force transmission	Poor gluteal and hamstring timing, quad dominance → dynamic collapse during propulsion	Reduced jump height, increased medial knee stress and overuse risk
Landing	Body decelerates and absorbs impact forces	High peak landing GRF → Increased stress on lower limb joints (knee, ankle)	Increased valgus angle → Higher risk of ACL and patellofemoral injuries	Weak hip abductors and trunk stability → medial knee collapse under high impact	Greater injury risk, poor shock absorption efficiency

Limitations

- Only male athletes were assessed, preventing sex-based comparisons highly relevant to ACL injury research
- Use of 2-D motion capture does not evaluate 3-D joint mechanics or knee valgus moments, which provide deeper biomechanical insights.
- Controlled lab conditions differ from real gameplay conditions that involve fatigue, agility, and variability in jump-landing direction.
- No assessment of muscle activation (EMG), foot pressure distribution, or trunk kinematics, making neuromuscular explanations more inferential.
- Only vertical GRF was examined, while AP (braking) and ML (shear) forces may contribute substantially to knee collapse.
- Participants performed planned landings, whereas unexpected landings in matches often produce greater valgus and injury risk.

Future Recommendations

- Increase sample size and include both male and female badminton players to identify sex-specific injury mechanisms.
- Use 3-D motion analysis and EMG to quantify knee loads, moment arms, and neuromuscular activation patterns.
- Assess GRF vector components (vertical, medial-lateral, anterior-posterior) for deeper interpretation of knee loading mechanics.
- Conduct studies under game-like and fatigue-based conditions to improve ecological validity.
- Examine foot/ankle mechanics, pelvic stability, and trunk positioning as part of the kinetic chain influence on valgus.
- Implement and compare neuromuscular training interventions (hip/core strengthening, plyometrics, balance training) with pre-post biomechanical outcomes.
- Explore differences between anticipated vs unanticipated landing scenarios, which are key ACL risk factors
- Include longitudinal follow-ups to determine if poor biomechanical profiles predict future injury incidence.

Conclusion

The current study illustrates that ground reaction forces affect knee valgus mechanics in a phase-dependent pattern throughout the badminton jump smash. Greater take-off knee valgus was correlated with diminished force generation at propulsive phases, which suggests poor coordination of the kinetic chain and impaired power transfer from the lower extremities. Conversely, greater valgus angles at landing were associated with greater peak impact forces, indicating greater mechanical stress on the medial knee structures and increased ACL injury, meniscus Injury (particularly medial meniscus) susceptibility. These opposed relationships highlight that knee valgus cannot be considered separately from the loading conditions induced during dynamic tasks. Sustaining proper frontal-plane control, in part through increased hip and trunk neuromuscular activation, seems vital not just for minimizing risk of injury but also for optimizing performance efficiency. Coaches and clinicians treating badminton players must hence put main stress on corrective movement approaches, focusing on proximal muscle strength, landing method, and general kinetic chain synchronization in order to encourage safer and more effective application of the jump smash. This study supports the inclusion of biomechanical screening and neuromuscular training in athlete development programs to protect long-term knee health and enhance explosive sport performance.

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