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Lower Extremity Stiffness and Linear Acceleration Performance in Basketball Players: Relationships Between Jump-Derived Stiffness Indices and Sprint Kinematics

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Background: Lower-extremity stiffness is a key determinant of sprint and jump performance; however, its relationship with acceleration-phase kinematics, including step frequency (SF), step length (SL), and ground contact time (GCT) remains poorly characterized in team sport athletes. This study examined associations between jump-derived stiffness and 10 m sprint kinematics in collegiate basketball players and compared kinematic profiles between faster and slower athletes.

Material/Methods: Fifteen male collegiate basketball players completed a 10 m sprint (splits: 0-5 m, 5-10 m, 0-10 m) with kinematics captured via dual high-speed cameras (240 fps). Lower-extremity stiffness was assessed using a portable force plate during countermovement jump (CMJ), drop jump (DJ), and hopping. Athletes were stratified by median split. Pearson correlations examined stiffness kinematic relationships within the fast group.

Results: The fast group demonstrated significantly greater 0-5 m SF (4.16 ± 0.34 vs 3.67 ± 0.39 Hz; $P = 0.026$) and SL (188.18 ± 10.87 vs 167.03 ± 15.71 cm; $P = 0.010$). SF showed near-perfect negative correlations with 0-5 m ($r = -0.99$) and 0-10 m sprint times ($r = -0.99$; both $P < 0.001$). CMJ vertical stiffness, hopping knee and ankle stiffness, and DJ knee stiffness yielded large to very large correlations with GCT, SF, and SL, respectively, but were nonsignificant ($P > 0.05$). No between-group stiffness differences were detected.

Conclusions: SF was the kinematic variable most strongly associated with early-phase acceleration. Stiffness kinematic correlations, although large in magnitude, failed to reach statistical significance in this small sample. Findings should be considered exploratory; larger longitudinal studies are required before jump-derived stiffness indices can be recommended for performance monitoring.

Keywords: basketball • sports • force potentiation

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Introduction

Linear sprint speed is a fundamental determinant of athletic performance across a wide spectrum of team sports. In basketball, football, soccer, and rugby, game play is characterized by frequent, short-distance sprints interspersed with changes of direction and brief recovery periods [1]. Crucially, team sport athletes rarely attain maximum sprint velocity during competition, with most sprints in these sports occurring over distances of 20 m or less [2-4]. Consequently, the ability to accelerate rapidly over short distances particularly within the initial 0-10 m represents a more ecologically relevant physical quality for team sport athletes than maximal velocity per se.

The 10 m sprint test has been extensively validated as a measure of early acceleration ability and has demonstrated strong associations with lower extremity strength and power output in team sport athletes [5,6]. Growing evidence suggests that the acceleration phase itself can be partitioned into biomechanically distinct subphases as early (approximately 0-5 m, or the initial 3 steps), mid, and late acceleration, with each phase characterized by different force application strategies, kinematic profiles, and neuromuscular demands [7,8]. Understanding the mechanics of these subphases is essential for designing targeted training interventions that address deficits in specific phases of acceleration.

Sprint kinematics, specifically step length (SL), step frequency (SF), and ground contact time (GCT), are the primary observable parameters used to characterize acceleration performance. During early acceleration, athletes operating from a standing start must overcome inertia by generating high ground reaction forces over relatively prolonged ground contact phases, before transitioning to shorter contact times and higher stride rates as velocity increases [9,10]. Identifying which of these parameters most strongly differentiates faster from slower athletes has direct implications for performance monitoring and sprint training prescription.

Lower extremity stiffness, broadly defined as the resistance of the musculotendinous system to deformation under load, is recognized as a key mechanical property governing both sprint and jump performance [11,12]. Athletes with greater lower extremity stiffness demonstrate enhanced storage and release of elastic potential energy during the stretch-shortening cycle, enabling more efficient force transmission during ground contact [13]. Prior research has consistently linked higher stiffness with faster sprint times and greater jump heights across diverse athletic populations [14-16].

Lower extremity stiffness can be conceptualized and quantified at multiple levels as vertical stiffness (K_vert), leg stiffness (K_leg), and joint stiffness (K_joint), with each requiring distinct testing protocols [17]. These include treadmill-based running assessments, force-plate-embedded sprinting tasks, and various jump-based tests, such as the countermovement jump (CMJ), drop jump (DJ), and bilateral hopping [18-20]. Although jump-based protocols are increasingly preferred over instrumented treadmills due to their greater practicality in field settings, no studies to date have simultaneously examined the relationships between multiple jump-derived stiffness indices (CMJ, DJ, and hopping) and phase-specific sprint acceleration kinematic sub-parameters (0-5 m and 5-10 m SF, SL, and GCT) in collegiate basketball players. The novelty of the present study lies specifically in this combination: a basketball-specific population, phase-partitioned kinematic outcomes, and a multi-task stiffness battery assessed concurrently. Stiffness kinematic associations are examined within the faster athlete subgroup as an exploratory boundary condition, as described in the Methods.

Moreover, recent investigations have highlighted important position-dependent differences in lower extremity stiffness among basketball players, with guards exhibiting systematically higher soleus stiffness compared with forwards, a pattern attributed to their greater involvement in explosive accelerations during game transitions [21]. These observations underscore the practical relevance of quantifying stiffness in basketball-specific contexts. However, the mechanistic link between stiffness assessed during jumping and specific kinematic features of acceleration remains to be established. Distinguishing K_vert, K_leg, and K_joint is particularly relevant for basketball athletes because each construct reflects a different mechanical demand encountered during basketball-specific game play rather than during continuous sprinting. K_vert, captured during a CMJ or hopping, reflects whole-body resistance to compression during repeated stretch-shortening cycles, such as defensive shuffles, repeated jumping under the rim, and rapid re-acceleration after deceleration. K_leg primarily characterizes spring-like behavior of the lower limb during running and bounding, which is engaged during transitional fast-break sprints. Joint-level stiffness (K_knee, K_ankle), in contrast, isolates the local mechanical contribution of individual joints during ground contact and is therefore most directly relevant to the standing-start, low-velocity, knee- and ankle-dominant impulse generation that characterizes early acceleration in basketball, rather than the block-start, high-velocity, hip-dominant mechanics of competitive sprinters. Establishing which of these stiffness constructs best aligns with phase-specific sprint kinematics in basketball players is therefore a basketball-relevant question and not simply an extension of sprint-population findings.

The purpose of this study, therefore, was 2-fold: (1) to identify the sprint kinematic variables most strongly associated with performance differences between faster and slower collegiate basketball players across 0-5 m and 5-10 m acceleration

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phases; and (2) to explore the relationships between jump-derived lower extremity stiffness measures (CMJ, DJ, and hopping) and sprint kinematics within the faster athlete subgroup (as an exploratory boundary condition to reduce kinematic heterogeneity). We hypothesized that SF and GCT would be the most strongly associated kinematic variables with performance during early acceleration, and that K_joint derived from jumping tasks would show significant associations with SF and GCT in the 0-5 m phase within the fast subgroup.

Material and Methods

Experimental Design

This study employed a correlational, cross-sectional design to examine the relationships between jump-derived lower extremity stiffness indices and sprint acceleration kinematics and to compare kinematic profiles between relatively fast and slow collegiate basketball players. The independent variables were lower extremity stiffness measures derived from CMJ, DJ, and hopping tasks (K_vert, K_knee, K_ankle). The dependent variables were sprint performance outcomes (split times at 0-5 m, 5-10 m, and 0-10 m) and their associated kinematic parameters (SL, SF, GCT).

All testing was conducted over 2 sessions separated by 5 hours of rest within a single day. Session 1 consisted of the 10 m linear acceleration test and kinematic data collection. Session 2 consisted of the lower extremity stiffness assessment battery. Participants were familiarized with all testing procedures during routine training sessions in the week preceding formal data collection.

Participants

Fifteen healthy male collegiate basketball players (age: 20.3 ± 1.4 years; height: 183.4 ± 7.6 cm; body mass: 81.9 ± 15.6 kg; competitive experience: 6.2 ± 2.1 years) from a university varsity program volunteered to participate. All participants were free from musculoskeletal injury and had not undergone surgical intervention in the 12 months preceding the study. Participants were excluded if they had a history of neurological conditions, lower extremity fractures, or ligamentous reconstructions that could affect sprint mechanics or force production. Written informed consent was obtained from all participants prior to data collection, in accordance with the ethical principles outlined in the Declaration of Helsinki.

Testing Procedures

All sessions were preceded by a standardized 15-minute warm-up consisting of 5 minutes of submaximal jogging, lower extremity dynamic stretching (leg swings, hip circles, walking lunges), and 3 progressive 20 m acceleration runs at 60%, 80%, and 95% of perceived maximum effort.

Sprint Assessment

Participants performed 2 maximal-effort 10 m sprint trials separated by 3 minutes of passive recovery. A standing-start position was adopted with the front foot placed 50 cm behind the timing gate start line, and athletes were permitted to choose their preferred lead foot [22]. Infrared timing gates (Dashr Systems, Lincoln, USA) recorded split times at 0-5 m, 5-10 m, and 0-10 m. The fastest trial was retained for analysis.

Kinematic Analysis

Two high-speed video cameras (Casio EX-FH100, 240 frames per second [fps]; Casio America Inc, Dover, NJ, USA) were positioned perpendicular to the running lane, 5 m from the sprinting plane, at distances of 2.5 m and 7.5 m from the start line to capture the 0-5 m and 5-10 m intervals, respectively [23]. Retroreflective tape markers (1.5 in wide) were affixed bilaterally to the first and fifth metatarsal heads to serve as toe-off and contact landmarks. All recordings were imported and analyzed using Silicon Coach Pro software (Silicon Coach Ltd, Dunedin, New Zealand). GCT was defined as the period from initial foot contact to toe-off of the ipsilateral foot. SL was defined as the horizontal distance from toe-off of one foot to the subsequent ipsilateral foot contact. SF was calculated as the reciprocal of step duration. GCT, SL, and SF were computed separately for the 0-5 m and 5-10 m intervals; interval means were calculated by averaging across all identifiable steps within each interval captured by the respective camera. Mean values across all steps within each interval were used for statistical analysis [23]. Intra-rater reliability of the manual frame-based identification of foot-contact, toe-off, GCT, SL, and SF was assessed by reanalysis of a randomly selected subset (approximately 20%) of trials by the same investigator on a separate day at least 7 days after the initial analysis. Intraclass correlation coefficients (2-way mixed model, absolute agreement) for GCT, SL, and SF were all greater than 0.90, indicating excellent intra-rater agreement and consistent with prior reports for 2-dimensional manual high-speed video analyses of sprint kinematics. Because all kinematic analyses were performed by a single trained investigator, formal inter-rater reliability could not be quantified within the present dataset; this constraint is explicitly acknowledged in the Limitations section. The use of 2-dimensional video analysis (rather than 3-dimensional motion capture) is a deliberate methodological choice that prioritizes ecological validity and field-based feasibility for collegiate basketball settings, but it inherently limits accuracy in identifying joint centers and out-of-plane motion; this constraint and its likely effect on the joint-stiffness estimates are discussed more critically in the Limitations section.

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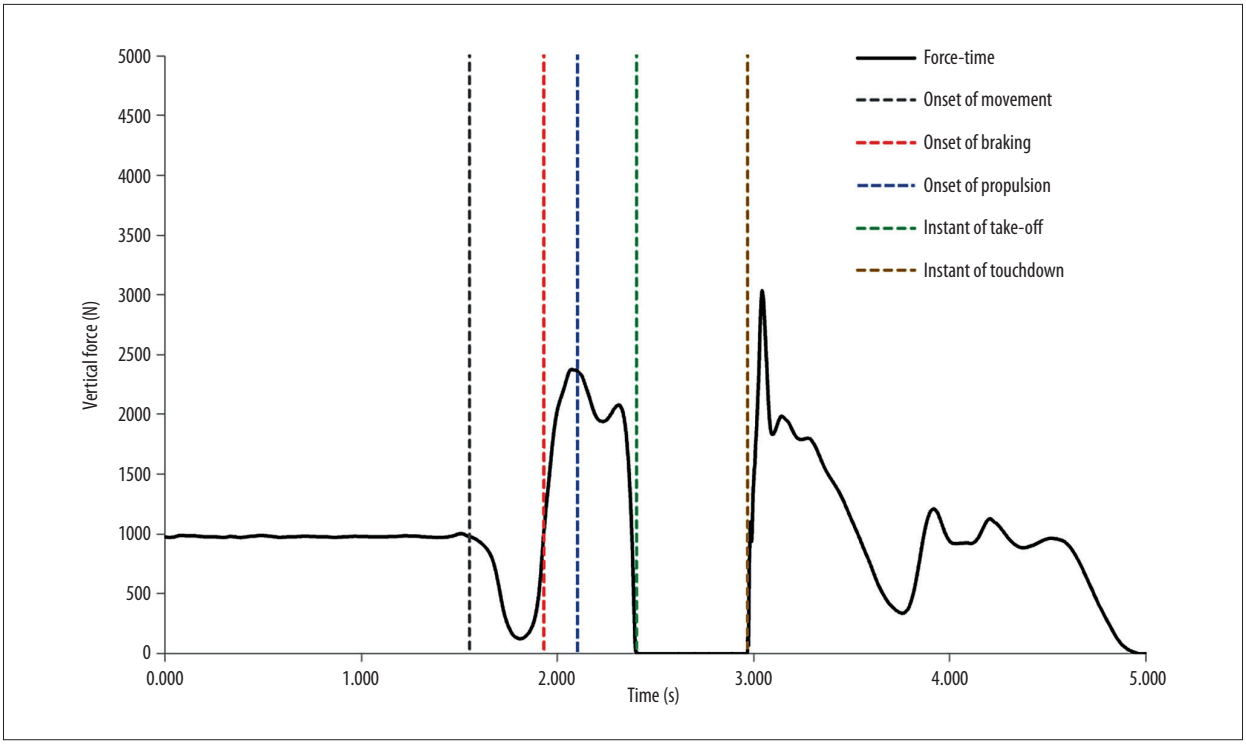

Figure 1. Vertical ground reaction force–time curve during a countermovement jump. Vertical stiffness (K_vert) during the CMJ was calculated as K_vert = F_peak / ΔL, where F_peak is the peak vertical ground reaction force recorded during the propulsion phase, and ΔL is the maximum downward displacement of the center of mass (CoM), derived by double-integration of the net force-time curve (Figure 2) [25,26].

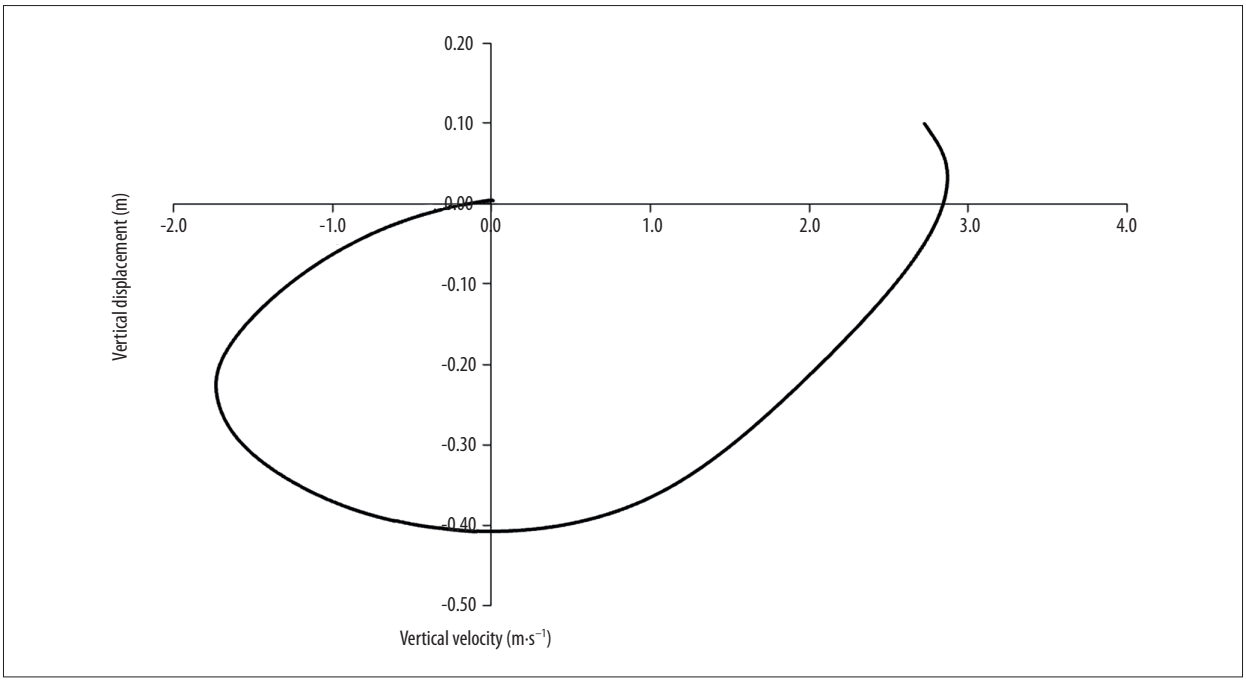

Figure 2. Phase portrait of center of mass (CoM) vertical displacement vs velocity during a countermovement jump.

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Lower Extremity Stiffness Assessment

All jump tests were performed on a portable force plate (Kistler Type 9260AA; Kistler Instrumente AG, Winterthur, Switzerland) sampling at 1000 Hz. Participants held a wooden dowel horizontally across the upper back throughout all jumps to minimize upper-extremity contributions to vertical impulse.

Countermovement Jump

Participants performed 2 maximal CMJ trials from a self-selected squat depth, with instructions to jump as high and as quickly as possible [24]. The CMJ consisted of 4 sequential phases identifiable from the vertical ground reaction force–time curve: unweighting (eccentric loading initiation), braking (peak eccentric force generation), propulsion (concentric push-off), and flight (**Figure 1)**. The phase portrait of vertical center of mass (CoM) displacement vs velocity illustrates the dynamic trajectory throughout the CMJ. During the eccentric phase, the CoM descends as downward velocity increases, reaching maximum displacement at zero velocity, marking the eccentric-to-concentric transition (**Figure 2**).

Drop Jump

Participants stepped off a box with a height of 0.3 m and were instructed to minimize contact time while maximizing jump height. Two trials were completed with 2 minutes of rest between trials. A simultaneous high-speed camera (240 fps) recorded sagittal-plane kinematics, with markers placed at the greater trochanter, lateral knee, lateral malleolus, and fifth metatarsal head [27]. K_joint (K_knee and K_ankle) was determined as the ratio of the change in net joint moment to the corresponding joint angular displacement from initial contact to the instant of maximal joint flexion [28]. DJ K_vert was calculated using the same formula applied during the CMJ: DJ K_vert = F_peak / ΔL, where F_peak is the peak vertical ground reaction force recorded during the propulsion phase of the DJ, and ΔL is the maximum downward displacement of the CoM derived by double-integration of the net force-time curve from initial contact to the instant of peak force [25,26]. The DJ force-time trace was processed using the analytical framework described by Pedley et al [47]; representative filtered data, ground contact period force, and CoM displacement profiles are illustrated in **Figure 3**. Specifically, the filtered DJ force-time trace (**Figure 3A**) was used to identify the 5 analytical landmarks defined by Pedley et al [47]: (1) initial ground contact, marking the start of the ground-contact period; (2) the impact peak, the first transient force peak occurring within the first approximately 30 milliseconds of contact; (3) the peak braking force, the maximum vertical force during the eccentric phase, prior to peak CoM displacement; (4) the force at peak CoM displacement, taken as the instantaneous force at the lowest point of the CoM trajectory and used to indicate the athlete's ability to generate stiffness through the lower limb during rebound; and (5) the peak propulsive force, the maximum force during the concentric push-off phase, with toe-off marking the end of the ground contact period. The braking phase (initial contact peak to CoM displacement) was operationally separated from the propulsion phase (peak CoM displacement to toe-off) on the basis of the CoM trajectory derived by double-integration of the net force–time signal, consistent with the Pedley et al workflow [47]. The mechanical "spring-like" behavior of the lower extremity during the DJ was further characterized by re-plotting the within-contact force–time data against the simultaneously derived CoM downward displacement, yielding a force-displacement (stiffness) curve (**Figure 3B**). DJ K_vert was operationalized as the slope of the linear regression of vertical ground reaction force on CoM downward displacement during the braking phase (ie, from initial contact to peak CoM displacement), in units of body weight per centimeter of CoM displacement, and additionally expressed in absolute units ($N \cdot kg^{-1} \cdot m^{-1}$) using the F_peak/ΔL formulation described above [25,26,47]. Within this framework, a curve approaching a single, near-linear loop indicates close-to-ideal spring-like behavior, whereas a curve in which the propulsive peak occurs substantially after peak CoM displacement reflects a loss of stiffness at peak displacement and a more concentric-dominant rebound strategy [47]. All DJ trials were inspected against these criteria prior to inclusion in the analyses.

Hopping Test

Participants performed bilateral vertical rebounds at a cadence of 2 Hz, guided by a digital metronome, for 10 consecutive seconds. Vertical stiffness was calculated identically to the CMJ protocol. Joint stiffness was computed from the simultaneous high-speed video and force plate data using the same K_joint algorithm applied during the DJ [28,29].

Statistical Analyses

Descriptive statistics are reported as mean ± standard deviation (SD). Participants were dichotomized into fast (n = 7) and slow (n = 8) groups based on a median split of their 10 m sprint time. Independent samples *t* tests were used to examine group differences in sprint performance, kinematic variables, and lower extremity stiffness measures. Pearson's product-moment correlation coefficients (r) were calculated within the fast group to assess the relationships between lower extremity stiffness indices and sprint kinematic variables. The magnitude of correlation coefficients was interpreted using the following benchmarks: trivial (< 0.1), small (0.1-0.3), moderate (0.3-0.5), large (0.5-0.7), very large (0.7-0.9), and near perfect (0.9-1.0) [30]. Effect sizes for between-group comparisons were calculated using Cohen's d, interpreted as small

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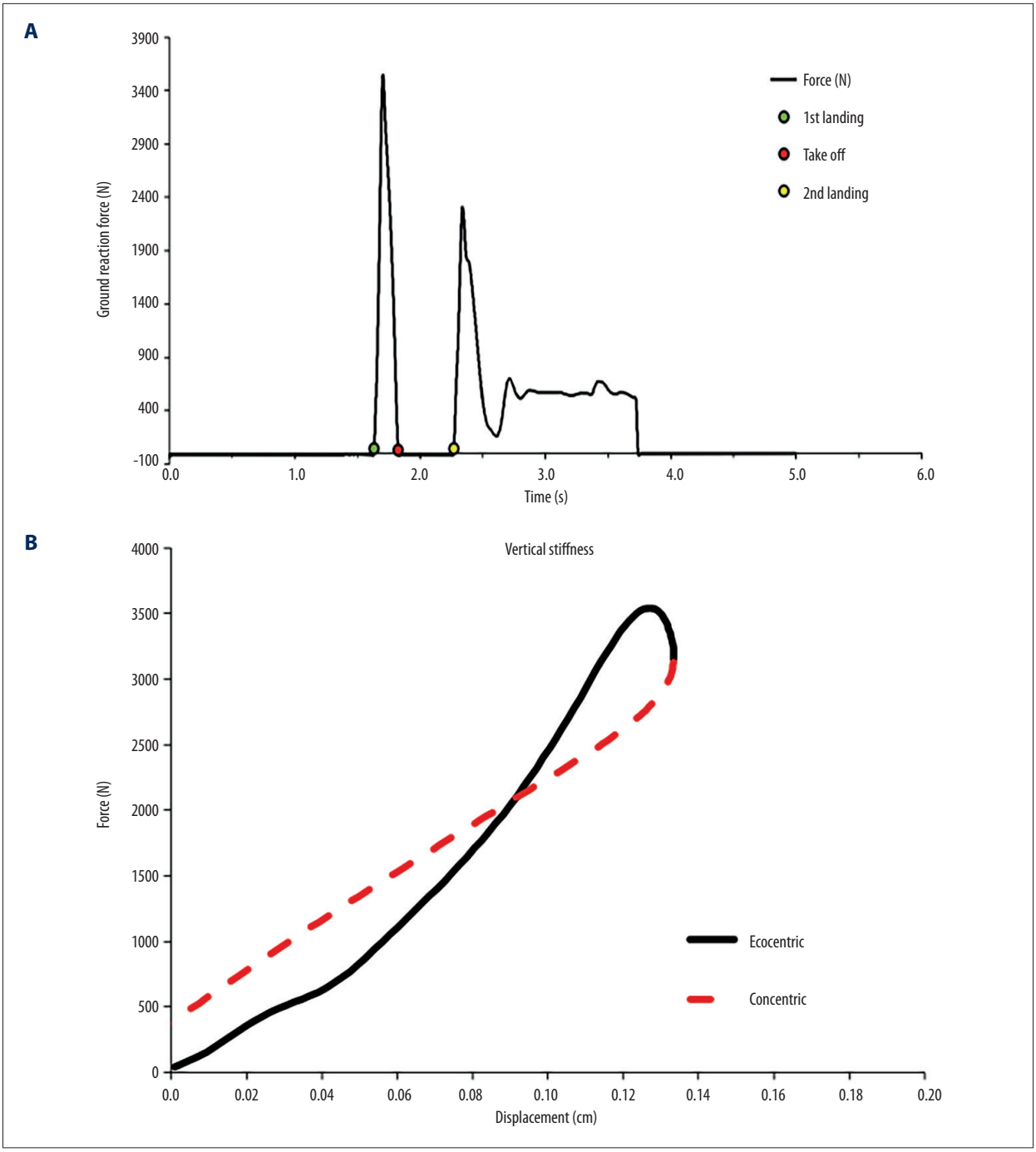

Figure 3. Vertical ground reaction force–time characteristics during the drop jump (DJ), derived using the force-plate analysis framework described by Pedley et al [47].

(0.2-0.5), moderate (0.5-0.8), and large (> 0.8). Post hoc statistical power analyses were conducted using G*Power (version 3.1; Heinrich Heine University, Düsseldorf, Germany) for both the independent samples *t* tests and Pearson correlation analyses. For independent samples *t* tests (total n = 15), power estimates were calculated assuming a large effect size ($d = 0.8$) at $\alpha = 0.05$, yielding a statistical power of 0.54. For Pearson correlation analyses conducted within the fast group (n = 7), power was estimated assuming a large effect size ($r = 0.5$) at $\alpha = 0.05$, yielding a statistical power of 0.30. The limited statistical power reflects the exploratory nature of this study and the inherent constraints of the sample size; findings should therefore be interpreted with caution and considered preliminary pending replication in larger cohorts. Given the large number

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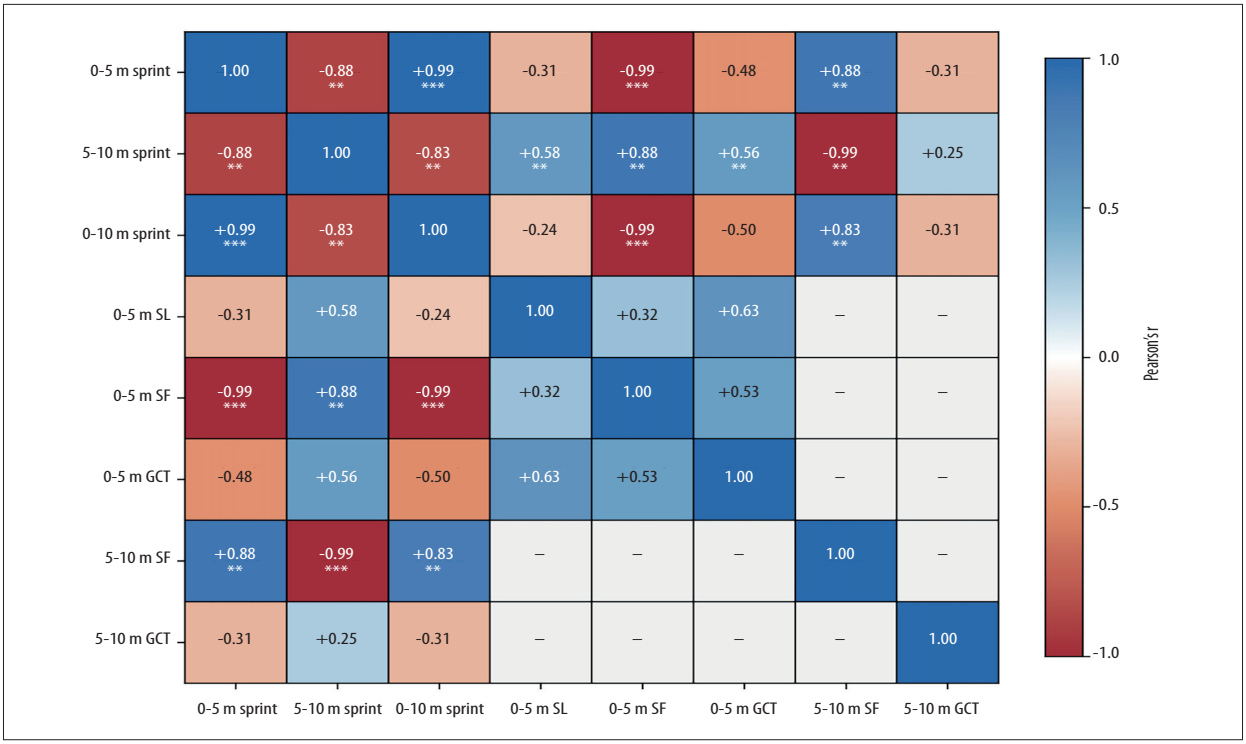

Figure 4. Pearson correlation matrix between sprint performance and acceleration kinematics in the fast group (n = 7).

Table 1. Intercorrelation matrix of 0-5 m kinematic variables in the fast group (n = 7).

	0-5 m SL (cm)	0-5 m SF (Hz)	0-5 m GCT (s)
0-5 m SL (cm)	1.00		
0-5 m SF (Hz)	0.32	1.00	
0-5 m GCT (s)	0.63 ($P = 0.13$)	0.53 ($P = 0.22$)	1.00

Abbreviations: SL, step length; SF, step frequency; GCT, ground contact time.

Table 2. Pearson correlations between lower extremity stiffness indices and sprint kinematic variables in the fast group (n = 7).

	0-5 m SL	0-5 m SF	0-5 m GCT	5-10 m SL	5-10 m SF	5-10 m GCT
CMJ K_vert	-0.35	0.04	-0.60 ($P = 0.15$)	-0.08	-0.10	-0.22
DJ K_vert	-0.01	-0.15	0.15	-0.52	-0.01	0.27
Hopping K_vert	0.24	-0.09	-0.40	0.09	-0.05	0.28
DJ K_knee	0.72 ($P = 0.07$)	0.34	0.41	0.44	-0.31	0.46
DJ K_ankle	0.35	-0.23	-0.16	0.47	0.14	-0.16
Hopping K_knee	-0.02	-0.62 ($P = 0.14$)	-0.22	0.33	0.48	-0.62
Hopping K_ankle	0.10	-0.59 ($P = 0.16$)	-0.11	0.26	0.38	-0.19

Abbreviations: SL, step length; SF, step frequency; GCT, ground contact time; CMJ, countermovement jump; DJ, drop jump; K_vert, vertical stiffness; K_knee, knee joint stiffness; K_ankle, ankle joint stiffness.

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Table 3. Comparison of sprint performance, kinematic variables, and lower extremity stiffness between fast and slow groups.

Variable	Fast group (n = 7)	Slow group (n = 8)	*P*	Cohen's d	Magnitude
0-10 m sprint time (s)	1.66 ± 0.06 (7% faster)	1.80 ± 0.09	0.006*	1.83	Large
0-5 m sprint time (s)	0.96 ± 0.07 (9% faster)	1.05 ± 0.07	0.038*	1.28	Large
5-10 m sprint time (s)	0.70 ± 0.01 (5% faster)	0.74 ± 0.03	0.018*	1.78	Large
0-5 m mean GCT (s)	0.13 ± 0.01	0.14 ± 0.01	0.26	0.62	Moderate
0-5 m mean SL (cm)	188.18 ± 10.87	167.03 ± 15.71	0.010*	1.56	Large
0-5 m mean SF (Hz)	4.16 ± 0.34	3.67 ± 0.39	0.026*	1.33	Large
CMJ K_vert ($N \cdot kg^{-1} \cdot m^{-1}$)	0.72 ± 0.15	0.74 ± 0.10	0.81	0.16	Trivial
DJ K_vert ($N \cdot kg^{-1} \cdot m^{-1}$)	2.52 ± 1.17	1.67 ± 0.52	0.11	0.93	Large
Hopping K_vert ($N \cdot kg^{-1} \cdot m^{-1}$)	7.70 ± 1.53	7.97 ± 2.68	0.81	0.12	Trivial

Abbreviations: GCT, ground contact time; SL, step length; SF, step frequency; CMJ, countermovement jump; DJ, drop jump; K_vert, vertical stiffness. Values are mean ± SD. * Significant at $P < 0.05$ (independent samples *t* test). Magnitude classification (Cohen's *d*): trivial (< 0.2), small (0.2-0.5), moderate (0.5-0.8), large (> 0.8).

of correlations examined across **Figure 4 and Tables 1, 2** (encompassing kinematic intercorrelations and stiffness kinematic associations), no formal multiplicity correction was applied; instead, a pre-specified primary set of correlations was defined a priori based on the study hypotheses: (1) 0-5 m SF and GCT as kinematic variables of interest, and (2) CMJ K_vert, hopping K_knee, and hopping K_ankle as primary stiffness indices. All remaining correlations should be regarded as exploratory and interpreted accordingly.

The rationale for restricting stiffness-kinematic correlations to the fast subgroup was to reduce kinematic heterogeneity and focus on the mechanical context in which higher sprint velocities are achieved; population-level stiffness-kinematic inference is not claimed. All analyses were performed using IBM SPSS Statistics (version 27.0; IBM Corp, Armonk, NY, USA). Statistical significance was set at $\alpha = 0.05$. The choice of a median-split dichotomization into fast and slow subgroups was made specifically to enable a within-faster-athlete exploratory analysis of the mechanical conditions associated with higher sprint velocities while maintaining a parsimonious comparison structure in this small cohort (n = 15). We acknowledge that median-splitting a continuous variable in such a small sample inevitably reduces statistical power, increases the risk of spurious correlations, and yields subgroup sample sizes (n = 7 and n = 8) that further inflate Type I and Type II error probabilities. We therefore explicitly emphasize throughout the manuscript that all subgroup-based correlations are exploratory and hypothesis-generating only. Because subgroup sample sizes (n = 7) result in wide confidence intervals around any reported correlation, even "large" or "very large" coefficients that fail to reach statistical significance must be interpreted with extreme caution and should not be over-read as biologically meaningful relationships in the absence of formal replication.

Results

Between-Group Comparisons in Sprint Performance and Kinematics

The fast group was significantly faster than the slow group across all sprint intervals: 0-10 m (7% faster; $P = 0.006$, $d = 1.83$), 0-5 m (9% faster; $P = 0.038$, $d = 1.28$), and 5-10 m (5% faster; $P = 0.018$, $d = 1.78$). Statistically significant between-group differences in sprint kinematics were restricted to the 0-5 m interval, where the fast group demonstrated significantly greater SL (188.18 ± 10.87 vs 167.03 ± 15.71 cm; $P = 0.010$, $d = 1.56$) and SF (4.16 ± 0.34 vs 3.67 ± 0.39 Hz; $P = 0.026$, $d = 1.33$). No significant group differences were observed for GCT in either the 0-5 m or 5-10 m intervals, nor for any lower extremity stiffness measure. Full descriptive statistics and between-group comparisons are presented in **Table 3**.

Correlations Between Acceleration Characteristics and Sprint Performance

Within the fast group, SF of 0-5 m showed near-perfect negative correlations with sprint times of both 0-5 m ($r = -0.99$, $P < 0.001$) and 0-10 m ($r = -0.99$, $P < 0.001$), indicating that athletes with

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higher SFs in the early phase were markedly faster over both the distances of 5 m and 10 m. A very large positive correlation was identified between SF of 5-10 m and both sprint times of 0-5 m ($r = 0.88$, $P < 0.001$) and 0-10 m ($r = 0.83$, $P < 0.05$), suggesting that decreasing SF in the mid-phase was associated with overall faster performance (**Figure 4**).

Each off-diagonal cell of **Figure 4** displays the exact Pearson r value together with its significance marker, so that every pairwise correlation reported below is directly traceable to the figure. The extremely high magnitude of the 0-5 m SF and sprint-time correlations ($r \approx -0.99$) reported within the small fast subgroup (n = 7) should be interpreted with extreme caution. Coefficients of this magnitude in such a small sample carry a substantial risk of statistical instability and overfitting, and are arithmetically near-deterministic given that SF, SL, and sprint time are biomechanically inter-related (split time = number of steps / mean SF). These near-perfect coefficients are therefore reported descriptively as evidence that early-phase SF tracks early-phase sprint time within the fast subgroup, but they should not be interpreted as evidence of an independent causal relationship; their generalizability requires confirmation in a larger, independent sample.

Intercorrelations Among 0-5 m Kinematic Variables

Within the fast group, 0-5 m GCT showed large positive correlations with both 0-5 m SL ($r = 0.63$, $P = 0.13$) and SF ($r = 0.53$, $P = 0.22$), indicating that athletes with longer ground contact phases also tended to exhibit greater SL and SF values in the early acceleration zone; however, neither association reached statistical significance (both $P > 0.05$ at n = 7) and should be interpreted as exploratory trends only. These intercorrelations are presented in **Table 1.**

Relationships Between Lower Extremity Stiffness and Sprint Kinematics

CMJ K_vert demonstrated a large negative correlation with 0-5 m GCT ($r = -0.60$, $P = 0.15$), indicating a large but nonsignificant negative association between CMJ K_vert and early-phase GCT at this sample size. Hopping K_knee and K_ankle both showed large negative correlations with 0-5 m SF ($r = -0.62$, $P = 0.14$ and $r = -0.59$, $P = 0.16$, respectively), indicating large but nonsignificant negative associations between K_joint during hopping and early-phase SF at this sample size. DJ K_knee showed a very large positive correlation with 0-5 m SL ($r = 0.72$, $P = 0.07$). No stiffness measure was significantly correlated with 0-10 m sprint time (r range: -0.09 to -0.16). Full correlation data are presented in **Table 2**. Notably, none of the between-group comparisons in lower extremity stiffness (CMJ K_vert, DJ K_vert, DJ K_knee, DJ K_ankle, hopping K_vert, hopping K_knee, hopping K_ankle) reached statistical significance at $\alpha = 0.05$ (**Table 3**), and all stiffness-kinematic correlations within the fast subgroup remained nonsignificant after accounting for the small subgroup size. This null pattern is itself an important finding: in this small basketball cohort, jump-derived stiffness indices did not discriminate fast from slow athletes at a population level, which directly tempers the practical implications that may be drawn from the exploratory within-subgroup correlations described above.

Discussion

The principal findings of this study are as follows: (1) SF in the 0-5 m phase was the most strongly associated kinematic variable with early acceleration performance in this sample of collegiate basketball players; (2) athletes in the fast group exhibited significantly greater SL and SF during the 0-5 m phase, but not during the 5-10 m phase; and (3) jump-derived lower extremity stiffness, while not significantly different between fast and slow groups overall, demonstrated meaningful exploratory correlations with specific kinematic variables in the faster athlete subgroup, most notably between CMJ K_vert and 0-5 m GCT, and between hopping K_joint and 0-5 m SF.

Our observation that SF rather than SL or GCT alone best discriminated fast from slow athletes during the 0-5 m phase aligns with prior kinematic analyses of field sport athletes [31,32]. Murphy et al [31] demonstrated that faster field sport athletes (football, rugby, soccer) exhibited approximately 9% higher SF and shorter GCTs during early acceleration compared with slower counterparts, a finding replicated in the present basketball-specific sample. Recent biomechanical investigations confirm that during the early acceleration phase (0-10 m), GCTs are typically 0.13 to 0.15 seconds, and SF increases rapidly before stabilizing near 4.5 to 5.0 Hz, consistent with the values observed in our fast group (4.16 ± 0.34 Hz) [33]. Notably, Hermansen et al [33] recently compared sprint and horizontal jump kinematics between sprinters and team sport athletes, confirming that team sport athletes showed systematically shorter SLs and higher SFs relative to sprinters across all sprint conditions, which is consistent with the standing-start mechanics and biomechanical constraints characteristic of basketball acceleration tasks.

The absence of significant between-group differences in 5-10 m SF and GCT, despite faster overall sprint times in the fast group, reflects a well-documented kinematic transition at approximately the 5 m mark [7,8]. Beyond this point, the mechanistic contribution of GCT to acceleration changes, with SL becoming the primary driver of velocity generation. This supports the partitioned training philosophy advocated by Mann [7], whereby early acceleration (0-5 m) training should emphasize SF and GCT optimization, while mid-acceleration (5-10 m) training should transition toward SL development.

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The present findings differ from studies using competitive sprinters, who typically exhibit longer SL and lower SF during the first steps because of the favorable postural mechanics afforded by starting blocks [7,8]. Our participants used a standing start, which restricts forward torso lean and necessitates sustained horizontal force application, likely explaining the reliance on higher SF in the very early phase. These starting condition differences must be considered when extrapolating kinematic norms from sprinter-based literature to basketball settings.

The absence of a significant correlation between any stiffness index and overall 10 m sprint time (r = -0.09 to -0.16) is consistent with earlier work by Bret et al [34], who reported that K_vert was significantly correlated with maximum speed (30-60 m) but not with acceleration-phase sprint times (0-30 m). This pattern suggests that the mechanical contribution of lower extremity stiffness to sprint performance is phase-dependent: stiffness is more critical for force production at high movement velocities (ie, maximal speed), whereas early acceleration is governed more by the ability to generate high horizontal impulses over extended ground contact phases. Supporting this interpretation, Seiferth et al [38] recently demonstrated in elite field sport athletes that the reactive strength index, a composite measure closely related to musculotendinous stiffness and stretch-shortening cycle efficiency, was significantly correlated with sprint performance in the 5-10 m, 10-20 m, and 20-30 m splits but showed no significant association with the initial 0-5 m phase, reinforcing the concept that stiffness-related mechanical qualities exert progressively greater influence as sprint velocity increases and ground contact durations shorten.

The large negative correlation between CMJ K_vert and 0-5 m GCT (r = -0.60, P = 0.15) is a large but nonsignificant exploratory association at this small subgroup size (n = 7) and should be interpreted strictly as a hypothesis-generating trend rather than as confirmatory evidence. The direction of the association—namely, that athletes with greater CMJ K_vert tended to exhibit shorter GCTs in the 0-5 m phase—is mechanistically consistent with the role of musculotendinous stiffness in reducing energy dissipation during rapid loading [11,13], but the present data do not provide statistical support for an established relationship. A recent investigation by Li et al [35] similarly demonstrated that K_vert derived from CMJ, calculated from peak ground reaction forces and CoM displacement, was a significant predictor of 30 m sprint time and rate of force development in collegiate sprinters, supporting the conceptual relevance of CMJ K_vert as a field-applicable indicator of explosive lower-limb function. This is further corroborated by He et al [43], who reported significant negative correlations between CMJ and squat jump kinematic variables and acceleration sprint performance in elite sprinters. Collectively, these prior reports raise the possibility that CMJ-derived K_vert may capture neuromuscular qualities relevant to early ground contact mechanics; however, given the nonsignificant exploratory nature of our own correlation, our data should be interpreted as preliminary and hypothesis-generating only, and CMJ K_vert should not be advocated as a validated monitoring tool for basketball-specific acceleration performance pending prospective confirmation in larger cohorts.

The large negative correlations between hopping K_knee and K_ankle and 0-5 m SF (r = -0.62 and r = -0.59, respectively) are large but nonsignificant exploratory associations (both P > 0.10 at n = 7) that should be interpreted as hypothesis-generating only. The direction of these trends is consistent with the conceptual notion that greater joint-level stiffness during repetitive hopping may permit more efficient force cycling in the early acceleration phase, but no firm inference about a higher step rate being driven by K_joint can be drawn from the present data. To the best of our knowledge, no prior study has simultaneously examined associations between hopping-derived K_joint and phase-specific sprint kinematic sub-parameters in collegiate basketball players, making these exploratory findings a novel contribution within this specific combination of population and outcomes. The positive correlation between DJ K_knee and 0-5 m SL (r = 0.72, P = 0.07), which, while not reaching conventional significance at this sample size, corroborates evidence that adult athletes rely more heavily on knee extension mechanics during early acceleration than do adolescent counterparts [36] and highlights the knee joint as a potential site for stiffness-related performance optimization in this population. These exploratory correlations also carry potential implications for training program design. Uzun et al [44] recently demonstrated that 8 weeks of plyometric training using optimal drop heights significantly improved reactive strength index, K_vert, and reactive braking force in junior male basketball players, indicating that structured DJ protocols are an effective means of elevating the jump-derived stiffness indices assessed in the present study. Similarly, a meta-analysis by Yan et al [45] confirmed that plyometric training significantly enhances sprint performance in youth basketball players, with improvements mediated in part through neuromuscular adaptations including increased stretch-shortening cycle efficiency and musculotendinous stiffness. These findings, taken together with the stiffness kinematic associations reported here, provide a mechanistic rationale for incorporating progressive plyometric loading into the training programs of collegiate basketball players with the specific aim of improving early-phase sprint mechanics.

Importantly, DJ K_ankle did not demonstrate significant correlations with any kinematic variable above the moderate range. This may reflect the distinct mechanical roles of the knee and ankle during the initial acceleration phase, where the knee contributes disproportionately to propulsive force generation

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while the ankle primarily serves an energy-transmission function [37]. Position-specific stiffness investigations have further suggested that basketball guards exhibit systematically higher soleus and plantar flexor stiffness compared with forwards, a pattern linked to their greater frequency of explosive accelerations during transition play [21]. Future studies should examine position-stratified stiffness-kinematic associations to refine training prescriptions for different positional roles. From a training intervention standpoint, Chang et al [46] demonstrated that resisted sprint training reduces SL and SF while increasing GCT during the loading phase, whereas assisted sprint training shortens contact time and increases SL, findings that offer complementary practical strategies for addressing the specific kinematic deficits identified in the slow group of the present study. Coaches may therefore consider pairing resisted sprint loads to develop propulsive impulse capacity with assisted overload conditions to target SF and contact time improvements within a periodized acceleration training framework.

A further methodological consideration relevant to the interpretation of the present stiffness data concerns the role of verbal encouragement and motivational feedback during explosive performance testing. Standardized verbal encouragement has been shown to substantially modulate jump and neuromuscular performance outcomes, with effects observed on jump height, peak power, ground reaction force, and reactive strength indices during CMJ, DJ, and hopping tasks [48]. Because all stiffness indices in the present study were derived from CMJ, DJ, and bilateral hopping protocols, between-trial and between-participant variability in motivational state, examiner-delivered encouragement, and athlete arousal during testing may have introduced non-trivial measurement noise into the stiffness estimates. Although our protocol used a standardized script and the same investigator across all sessions, the absence of formal monitoring of verbal-encouragement intensity is acknowledged as a potential confounder of the jump-derived stiffness measurements and may, in part, explain the relatively wide variability and the failure of stiffness measures to discriminate fast from slow athletes at a population level.

A second contextual factor that may have influenced the stiffness kinematic associations observed here is the cumulative musculoskeletal loading history of collegiate basketball players. Subclinical microtraumas of the patellar tendon, Achilles tendon, plantar fascia, and lower-extremity musculature are common in basketball populations, even in the absence of self-reported injury or symptomatic presentation, and recent imaging-based evidence has highlighted that such low-grade tissue alterations can meaningfully influence local mechanical properties and jumping biomechanics in asymptomatic athletes [49]. Although our exclusion criteria removed athletes with overt musculoskeletal injury or surgery within the prior 12 months, asymptomatic tendinopathic or muscle-architecture changes were not formally screened in the present cohort. Such subclinical tissue heterogeneity could plausibly contribute to the between-athlete variability in CMJ, DJ, and hopping stiffness, attenuating between-group differences and biasing the stiffness-kinematic correlations within the small fast subgroup. This potential confounder is acknowledged in the Limitations section.

Finally, the generalizability of the present findings to female basketball athletes is uncertain because only male collegiate players were enrolled. Recent investigations have documented systematic sex-related differences in lower-extremity neuromuscular and biomechanical adaptations relevant to sprint acceleration and jump-derived stiffness, including differences in muscle and tendon stiffness, reactive strength, sprint force–velocity profile, ground reaction force impulse, and stretch-shortening cycle behavior during jumping and sprinting tasks in team-sport athletes [50,51]. Position-stratified data in women's basketball additionally indicate sex-by-position interactions in lower-extremity stiffness profiles that are not directly inferable from male cohorts [21]. Two additional lines of evidence further support this concern. First, in elite team-sport athletes, Kilci [50] recently reported significant sex-based differences between male and female soccer players in sprint performance (effect size [ES] = 2.34), reactive strength index (ES = 0.75) and muscle stiffness (ES = 1.02), with male players exhibiting higher reactive strength index and stiffness values that were also more strongly associated with sprint and explosive-performance outcomes than in their female counterparts. This pattern suggests that the neuromechanical pathways linking jump-derived stiffness to sprint performance, the central focus of the present study, may operate with different magnitudes and associations between sexes, and cannot be assumed identical in female team sport athletes. Second, Galantine et al [51] demonstrated that the sprint force–velocity profile differs systematically between men and women: even after allometric scaling for body mass and fat-free mass, residual sex differences in theoretical maximal horizontal force, maximal velocity and maximal power output during 35 m maximal sprints persisted, indicating that qualitative physiological factors (rather than purely anthropometric ones) underlie sex-related differences in sprint mechanics. Together with [21], these data reinforce the conclusion that the male-only stiffness-kinematic associations reported here should not be directly extrapolated to female basketball athletes. Direct extrapolation of the early-acceleration kinematic and stiffness kinematic patterns reported here to female collegiate basketball athletes is therefore not warranted, and replication in female cohorts and in mixed-sex designs that explicitly model sex as a moderator is required. This limitation is also stated in the Limitations section.

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Limitations

Several limitations should be noted. The small sample size (n = 15) resulted in limited statistical power, and all findings should be regarded as exploratory pending replication in larger cohorts. The cross-sectional design precludes causal inference, and the restriction to male collegiate players from a single institution limits generalizability. Joint stiffness was estimated from 2-dimensional video, which may introduce error relative to 3-dimensional motion capture. Additionally, positional role, training history, and fatigue status were not controlled, and their potential influence on the observed stiffness-kinematic associations cannot be excluded. Several additional limitations should be emphasized. First, the dichotomization of an already small cohort (n = 15) into fast (n = 7) and slow (n = 8) subgroups via a median split materially reduced statistical power for both between-group comparisons and the within-fast-subgroup correlation analyses, and increased the risk of both Type I and Type II error; the "large" and "very large" correlations reported within the fast subgroup that did not reach statistical significance must therefore be interpreted only as exploratory hypothesis-generating signals. Second, although a pre-specified primary set of correlations was defined a priori, the overall number of correlations examined across **Figure 4 and Tables 1, 2** was substantial relative to the subgroup sample size, and no formal multiplicity correction was applied; reported *P* values for the secondary, exploratory associations should accordingly be treated as nominal. Third, the use of 2-dimensional sagittal-plane high-speed video (rather than 3-dimensional motion capture) for estimating joint angular displacement during the DJ and hopping tasks inherently constrains the accuracy of joint-stiffness estimates because of the absence of out-of-plane motion data, parallax, and dependence on manual marker identification; this is an important methodological constraint that should temper any joint-level mechanistic interpretation. Fourth, formal inter-rater reliability of the manual video analysis could not be quantified within the present dataset because all kinematic analyses were performed by a single trained investigator (intra-rater reliability is described in the Methods). Fifth, asymptomatic subclinical microtraumas of the patellar tendon, Achilles tendon, plantar fascia and lower-extremity musculature were not formally screened (eg, via imaging) and may have contributed unmeasured between-athlete variability in stiffness measurements [49]. Sixth, verbal encouragement and motivational state during the explosive performance tests were not quantitatively monitored and may have introduced residual measurement noise into the CMJ, DJ, and hopping stiffness indices [48]. Seventh, only male collegiate basketball players were enrolled; given the documented sex-related differences in muscle stiffness and reactive strength characteristics in elite team sport athletes [50] and in the sprint force–velocity profile even after controlling for body composition [51], the generalizability of these findings to female basketball athletes is uncertain, and replication in female and mixed-sex cohorts is required.

Conclusions

This exploratory study suggests that SF was the kinematic variable most strongly associated with 0-5 m linear acceleration performance in this small sample of male collegiate basketball players, while SL showed comparatively stronger associations in the 5-10 m phase. Jump-derived lower-extremity stiffness assessed via the CMJ, DJ, and hopping protocols did not differ significantly between fast and slow athletes, and the within-fast-subgroup stiffness-kinematic correlations did not reach statistical significance; these correlations should therefore be regarded as exploratory and hypothesis-generating only. We consequently cannot recommend the use of CMJ-derived K_vert, or hopping-derived K_joint, as validated monitoring tools for acceleration performance in basketball players on the basis of the present data. At most, the present results identify CMJ K_vert and hopping K_knee and K_ankle as candidate indices that warrant prospective evaluation in larger longitudinal cohorts before any practical monitoring application is considered. Findings should be regarded as preliminary and bounded to the studied context: a cross-sectional, correlational design; male collegiate basketball players from a single institution; and subgroup-based correlation analyses in a small fast athlete group (n = 7). Future research should examine the longitudinal effects of stiffness-focused training interventions (eg, plyometric or resisted sprint protocols) on stiffness indices and sprint kinematic outcomes in team sport athletes.

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Ethical Approval

The study protocol was reviewed and approved by the Institutional Review Board of China Medical University & Hospital, Taichung, Taiwan (protocol number: CMUH114-REC3-237).

Institution Where Work Was Done

China Medical University, Taichung, Taiwan.

Patient Consent/Permission

Written informed consent was obtained from all participants prior to data collection, in accordance with the ethical principles outlined in the Declaration of Helsinki. No individually identifiable patient data are reported in this manuscript.

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Declaration of Figures' Authenticity

All figures submitted have been created by the authors who confirm that the images are original with no duplication and have not been previously published in whole or in part.

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