

Associations between spike velocity and physical characteristics in elite sitting volleyball players: a cross-sectional study

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Research Article

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Abstract

Background

Spike velocity is a key component of attacking performance in sitting volleyball, but its physical correlates remain unclear. This study examined associations between spike velocity and anthropometric characteristics, anaerobic performance, and physical fitness in elite players.

Methods

Thirty elite sitting volleyball players (16 men and 14 women) performed six standardized maximal-effort spike trials and a comprehensive assessment of anthropometry, arm-crank anaerobic performance, upper-body strength and power, trunk function, and sport-specific movement performance. Between-sex differences, Pearson correlations with Benjamini–Hochberg correction, and an exploratory multiple linear regression were calculated.

Results

Men achieved a higher spike velocity than women (67.22 ± 6.74 vs. 51.51 ± 6.04 km/h; Hedges' $g = 2.38$, $p < 0.001$). After correction for multiple testing, spike velocity showed strong positive correlations with seated vertical grip reach ($r = 0.80$), sitting height ($r = 0.76$), handgrip strength ($r = 0.75$), one-repetition maximum bench press ($r = 0.74$), and seated medicine-ball chest-pass distance ($r = 0.70$; all adjusted $p < 0.001$). Moderate positive correlations were observed for hand span, seated rotational medicine-ball throw, and absolute arm-crank peak and mean power ($r = 0.51$ – 0.69 ; adjusted $p \leq 0.009$). The exploratory regression model explained 77.3% of the variance in spike velocity (adjusted $R^2 = 0.736$); seated vertical grip reach and bench press had positive coefficients, peak power had a negative coefficient, and rotational throw was not independently associated with spike velocity.

Conclusions

Seated anthropometric dimensions and general upper-body strength were most closely associated with maximal spike velocity. These findings support their combined use in athlete profiling, but the pooled mixed-sex associations and exploratory regression results require cautious interpretation.

Background

Sitting volleyball is a Paralympic net sport in which athletes perform volleyball-specific technical and tactical actions while moving across the court in a seated position. Under the official rules, restrictions on lifting the body from the court while playing the ball distinguish sitting volleyball from its standing counterpart [1]. Because the conventional standing approach and jump are absent, lower-limb propulsion

contributes less, placing greater demands on seated positioning, floor-based movement, trunk control, and upper-extremity function. Athletes also have different types and severities of eligible physical impairment and are currently classified as VS1 or VS2. Consequently, anthropometric and physical performance characteristics may interact with impairment-related functional limitations to influence sport-specific performance, and physical profiles may vary by competitive level and sex [2–6].

Attacking effectiveness is central to success in elite sitting volleyball. Match analyses indicate that attack effectiveness and other offensive actions distinguish winning from losing teams, whereas seated vertical reach and impairment-related functional characteristics may influence game performance [2, 7]. The spike is the principal forceful attacking action and is intended to direct the ball rapidly and accurately into the opponent's court. Although attack success also depends on set quality, attack direction, block organization, ball placement, and tactical decision-making, ball velocity is an objective and readily quantifiable component of spike performance. Greater velocity may reduce the time available for opposing blockers and floor defenders to perceive the ball trajectory and organize an effective response. Evidence from standing volleyball further shows that the spike involves high shoulder and elbow angular velocities, forces, and torques and that arm-swing technique and ball-to-hand contact influence the mechanics of the action [8–13].

The volleyball spike belongs to a broader family of overhand striking and throwing actions that includes the volleyball serve, tennis serve, team-handball throw, and baseball pitch. These actions generate high distal-segment and ball velocities through coordinated multisegmental motion rather than the isolated action of a single joint or muscle group. A broadly proximal-to-distal organization has been described, in which motion is transferred from the trunk and proximal upper-limb segments toward the forearm and hand, although the precise sequence depends on the task and on how joint and segmental events are defined [14, 15]. Direct comparisons of the team-handball throw, tennis serve, and volleyball spike have identified shared upper-body coordination patterns alongside task-specific differences in trunk, shoulder, elbow, and wrist kinematics [16]. Baseball pitching research likewise indicates that pelvis and upper-torso orientation, rotational velocity, and the timing of trunk rotation are associated with ball velocity and upper-extremity loading [17, 18]. In sitting volleyball, restricted lower-limb energy generation may increase the relative importance of initiating and transferring motion through the trunk and upper extremities.

Anthropometric characteristics may shape the spatial and mechanical conditions under which a sitting volleyball spike is performed. Sitting height and seated vertical grip reach may influence attainable contact height, the ability to strike above the net, and the effective path over which the striking arm can accelerate. Hand span may also affect hand–ball interaction and ball control, although its direct contribution to spike velocity remains unclear. Previous sitting volleyball research has shown that arm reach and the heights attained in block and spike positions are related to anaerobic and field-test performance, whereas seated vertical reach has been associated with game performance and sport-specific floor movement [2, 5, 19]. More directly, greater vertical reach facilitated a higher ball-impact position during the sitting volleyball serve, and impact height contributed to serve velocity [20]. Tennis

research similarly indicates that body height, sitting height, arm dimensions, body mass, and contact height may be associated with serve velocity, although the relevant predictors vary by sex, age, and playing level [21–25]. These findings support examining seated reach dimensions and hand characteristics in relation to spike velocity while recognizing that anthropometry may act partly through contact position and technique.

Upper-body strength and power may provide the force-generating foundation for a high-velocity spike. In standing volleyball players, spike velocity has been associated with the concentric strength of the dominant shoulder internal rotators and elbow flexors and extensors, highlighting the relevance of the muscles that directly accelerate the striking arm [9]. Greater muscular strength may improve force–time characteristics and provide a larger force reserve for explosive sporting actions [26]. Force–velocity characteristics derived from ballistic bench-press testing and other performance profiles have also been associated with spike and serve velocity in top-level volleyball players [11, 27]. Team-handball research likewise links overarm throwing velocity with one-repetition maximum (1RM) bench press, bar velocity, peak power, fat-free mass, and upper-body power [28, 29]. However, longitudinal observations in professional female volleyball players indicate that changes in general strength and medicine-ball throwing performance do not necessarily correspond to changes in spike velocity [30]. Handgrip strength, 1RM bench press, and seated medicine-ball chest-pass performance may therefore provide complementary indicators of general, maximal, and explosive upper-body capacity, but none reproduces the unilateral, high-velocity coordination demands of the spike.

Trunk function may be particularly relevant in sitting volleyball because the trunk contributes to postural control, body positioning, rotation, and the transfer of motion toward the striking arm. Research on overhand striking and throwing emphasizes the importance of coordinated trunk and upper-limb sequencing for generating distal-segment velocity [14, 16–18]. However, field tests capture different aspects of trunk function. Curl-up and back-extension tests primarily assess dynamic muscular endurance, whereas a seated rotational medicine-ball throw requires rapid trunk rotation coordinated with arm movement. Side medicine-ball throw performance has been associated with trunk and whole-body physical capacities in male and female athletes [31], and seated rotational mobility and power have been linked to overarm throwing velocity [32]. More recently, rotational medicine-ball throw performance has been associated with measured trunk-rotator strength, supporting its use as a functional indicator of rotational capacity [33]. Nevertheless, throwing distance is also influenced by release velocity, release angle, body dimensions, and technique and should not be interpreted as a direct measure of muscular power.

Anaerobic performance and sport-specific movement ability represent additional dimensions of the sitting volleyball physical profile. The arm-crank Wingate Anaerobic Test (WAnT) assesses the capacity to generate and sustain high upper-body power, whereas short sprints, multidirectional movement tests, and speed-endurance tasks assess the ability to reposition rapidly on court. In elite sitting volleyball players, WAnT outcomes have been associated with short-distance sprinting, agility, speed endurance, seated medicine-ball chest-pass performance, and selected game-performance measures [19]. Field-

fitness measures have also been associated with coach-rated sitting volleyball performance [34], and male and female national-team players have shown substantial differences in power- and speed-oriented field tests [3]. Comparisons between national- and league-level players further suggest that physical-test profiles reflect competitive level [4], whereas anthropometric and physical fitness characteristics have been related to floor-based sprint performance [5]. These findings support the relevance of anaerobic and movement capacities to overall sitting volleyball performance. However, their relationships with the velocity of a single standardized maximal spike remain uncertain because the tests differ in duration, movement pattern, and technical specificity.

Despite growing interest in sitting volleyball performance, the available evidence remains limited and methodologically heterogeneous. A scoping review identified only a small number of studies assessing physical fitness in sitting volleyball and highlighted substantial variation in testing protocols and outcome measures [6]. Existing studies have primarily examined anthropometric profiles, classification, field-test performance, game efficiency, competitive level, or serve velocity [2, 4, 5, 19, 20, 34]. To our knowledge, no previous study has simultaneously examined seated anthropometry, arm-crank anaerobic performance, upper-body strength and power, trunk function, and sport-specific movement performance in elite male and female sitting volleyball players. Therefore, this study aimed to examine the associations between spike velocity and anthropometric characteristics, anaerobic performance, and physical fitness in elite sitting volleyball players. We hypothesized that greater seated reach dimensions, upper-body strength and power, rotational throwing performance, and absolute anaerobic power would be associated with greater spike velocity, whereas shorter completion times in sport-specific movement tests would be associated with greater spike velocity.

Methods

Participants

Thirty elite sitting volleyball players from the Chinese men's and women's national teams were recruited during a national-team training camp before the 2026 Sitting Volleyball World Championships in Hangzhou, China. The sample included 16 men (age: 29.15 ± 7.73 years; training experience: 11.25 ± 6.92 years) and 14 women (age: 34.16 ± 6.89 years; training experience: 14.25 ± 6.45 years). According to the World ParaVolley classification system, 27 participants were classified as VS1 and three as VS2. All participants had at least three years of international competition experience. The required sample size was estimated a priori using G*Power software (version 3.1) with the "Exact tests—Correlation: Bivariate normal model" procedure. Assuming a correlation coefficient of $r = 0.45$ [9, 20], a two-tailed α of 0.05, and statistical power of 0.80, the minimum required sample was 29. To allow for potential withdrawal or incomplete data, 30 participants were recruited. All participants provided written informed consent before participation. The study was approved by the Beijing Sport University Human Participants Review Board (no. 2025195H) and conducted in accordance with the Declaration of Helsinki.

Design and procedures

Participants completed one familiarization session and three testing sessions at the Shanghai Special Olympics Competition and Training Center on four separate days, with 48 h between consecutive sessions. All sessions were conducted at approximately the same time of day within a 2-h window. Participants were instructed to refrain from strenuous physical activity for 48 h before each session and to maintain their usual diet and hydration habits. Before each testing session, participants completed a standardized warm-up consisting of specific mobility exercises and dynamic stretching. Assessments were performed in the order presented below and arranged in accordance with National Strength and Conditioning Association (NSCA) recommendations to minimize the potential influence of fatigue on subsequent tests [35]. A rest interval of 2–5 min was provided between tests. During the first testing session, participants completed the anthropometric assessments, handgrip strength test, 1RM bench press test, seated medicine-ball chest pass, and seated rotational medicine-ball throw. During the second testing session, they completed the spike velocity test, 5-m forward and backward sprint tests, modified agility T-test, speed-endurance test, curl-up test, and back-extension endurance test. During the third testing session, participants completed the 30-s WAnT.

Spike velocity test

Spike velocity was measured using a radar gun (Speedster II; Bushnell, Overland Park, KS, USA). Ball model (V5M5000; Molten Corporation, Hiroshima, Japan) and inflation pressure were standardized across trials. After three submaximal practice spikes, each participant performed six maximal-effort spike trials, each comprising a preparatory movement followed by an overhand striking action [9, 30]. A 1-min rest interval was provided between trials. To standardize the testing conditions, an experienced setter provided consistent sets, and participants were instructed to direct each spike toward a predefined diagonal target zone (Fig. 1). A single experienced operator aligned the radar gun with the ball trajectory at the height of ball contact. While the trigger was activated, the radar gun continuously tracked ball velocity, and the highest velocity detected during each trial was recorded [20]. The highest velocity achieved across the six valid trials was retained for analysis and expressed in kilometers per hour (km/h).

Anthropometric assessment

Anthropometric measurements were obtained by an International Society for the Advancement of Kinanthropometry (ISAK)-certified operator in accordance with the International Standards for Anthropometric Assessment [36], with adaptations for participants with motor disabilities where necessary [37]. Body mass was measured using a calibrated wheelchair scale (Seca 677; Seca GmbH & Co. KG, Hamburg, Germany), and standing height was measured using a measuring rod (Seca 220; Seca GmbH & Co. KG, Hamburg, Germany). Body mass index (BMI) was calculated as body mass divided by height squared (kg/m^2). To reflect the sport-specific playing posture, seated anthropometric

measurements were obtained with participants seated on the floor and their lower limbs extended [38, 39]. Sitting height and seated vertical grip reach were measured using a Harpenden anthropometer (Holtain Ltd., Crymych, Pembrokeshire, UK). Sitting height was defined as the vertical distance from the vertex of the head to the floor. Seated vertical grip reach was defined as the maximal vertical distance from the tip of the third digit (dactylion III) to the floor with the arm fully extended overhead. Participants maintained a hip angle of approximately 90° throughout the measurements. Hand span was measured as the maximal distance between the tip of the thumb (dactylion I) and the tip of the little finger (dactylion V), with the hand fully spread [5, 20].

Anaerobic performance test

Anaerobic performance was assessed using a 30-s WAnT performed on an arm-crank ergometer (LODE Angio; Lode BV, Groningen, the Netherlands) with the Wingate Anaerobic Software Package (Ergometry Manager; Lode BV, Groningen, the Netherlands). The ergometer was firmly secured to a wall-mounted gymnastic ladder, and its axis of rotation was aligned with the participant's glenohumeral joints. The protocol comprised a 2-min warm-up at 60 rpm and 50 W, a 1-min active recovery period, and a 30-s all-out arm-cranking test against a braking torque normalized to body mass [40, 41]. The torque factor was set at 0.55 N·m·kg⁻¹ for male participants and 0.54 N·m·kg⁻¹ for female participants [42]. Participants were instructed to crank as rapidly as possible from the start and received strong verbal encouragement throughout the 30-s effort. Peak power (PP), mean power (MP), relative peak power (rPP), relative mean power (rMP), and fatigue index (FI) were recorded. PP and MP were expressed in watts (W), whereas rPP and rMP were normalized to body mass and expressed in watts per kilogram (W·kg⁻¹). FI represented the decline in power from PP to the lowest recorded power output and was expressed as a fatigue slope in watts per second (W·s⁻¹).

Upper-body strength and power tests

1) Handgrip strength. Handgrip strength was assessed using a hydraulic hand dynamometer (SH5001; Saehan Corporation, Masan, Republic of Korea). Participants were seated with the tested elbow flexed to 90° and held close to the trunk. They were instructed to squeeze the dynamometer as forcefully as possible until a verbal stop signal was given. Three maximal trials were performed with each hand, with a 2–5-s rest interval between trials [34]. The highest value obtained with the dominant spiking hand was retained for analysis and expressed in kilograms (kg).

2) 1RM bench press. The 1RM bench press test was conducted in accordance with the protocol recommended by the NSCA [35]. Participants lay supine on a standard bench with the head, shoulders, and buttocks remaining in contact with the bench throughout each attempt. The warm-up comprised six repetitions at approximately 60% of the estimated 1RM followed by three repetitions at approximately 80% of the estimated 1RM. Participants then completed up to five attempts to determine their individual 1RM. The load was progressively increased by 5–10% until the greatest load that could be lifted once with proper technique was identified. Rest intervals of 2 min were provided between warm-up sets and 3

min between 1RM attempts. The highest successfully lifted load was retained for analysis and expressed in kilograms (kg).

3) Seated medicine-ball chest pass. The test was conducted according to previously described procedures [3, 43]. Participants sat on the floor with their backs against a wall, legs extended, and feet approximately 60 cm apart. Holding a 3-kg medicine ball with both hands in front of the chest and the forearms parallel to the floor, participants threw the ball straight forward as forcefully and as far as possible while keeping their backs in contact with the wall. Two maximal trials were performed, with a 45–60-s rest interval between trials [5, 44]. The greatest distance was retained for analysis and recorded in centimeters (cm).

Trunk function tests

1) Curl-up test. Participants lay supine on a mat with their knees flexed, the soles of their feet flat on the mat, their arms alongside the trunk, and their fingers fully extended on the mat [45]. An investigator stabilized the lower limbs, or residual limb(s) in participants with lower-limb amputation, to maintain knee flexion. Participants flexed the trunk until the inferior angles of the scapulae lifted from the mat and then returned to the starting position [5]. They completed as many valid curl-ups as possible within 30 s, and the total number of correctly completed repetitions was recorded.

2) Back-extension endurance test. The protocol was adapted from the back-extension endurance test described by Lanning et al. [46]. Participants lay prone on a testing table with the iliac crests aligned with the edge of the table. The pelvis and lower limbs, or residual limbs where applicable, were secured using straps, with additional manual stabilization provided when necessary. The upper body was initially supported on a stool, and the hands were placed behind the head. At the start signal, participants raised the trunk to a neutral position and then lowered it to approximately 45° of flexion, completing as many repetitions as possible within 30 s. Only repetitions in which both positions were reached were counted, and the total number of valid repetitions was recorded.

3) Seated rotational medicine-ball throw. The protocol was adapted from previously described side medicine-ball throw procedures [31, 32]. Participants sat behind the starting line in a side-on position with both knees fully extended. Holding a 3-kg medicine ball with both hands in front of the abdomen, they rotated the trunk away from the throwing direction and then rapidly reversed the movement to throw the ball diagonally forward as far as possible. Three maximal trials were performed in each direction, with a 45–60-s rest interval between trials. Distance was measured from the starting line to the first point at which the ball contacted the floor. The best distance achieved in each direction was recorded in centimeters, and the mean of the two values was retained for analysis.

Sport-specific movement tests

1) 5-m forward and backward sprint tests. The tests followed the procedures described by Cavedon et al. [5]. For the forward sprint, participants began from a stationary seated position behind the starting line

and moved forward over 5 m as quickly as possible (Fig. 2A). For the backward sprint, participants began from the same position and moved backward over 5 m as quickly as possible. The fastest time (s) obtained in each direction was retained separately for analysis.

2) Modified agility T-test. The protocol was adapted from the modified agility T-test described by Sassi et al. [47]. Participants started from a seated position behind line A and moved 5 m forward to cone B, touching its base with the right hand. They then moved 3 m laterally to the left toward cone C and touched its base with the left hand. Next, participants moved 6 m laterally to the right toward cone D and touched its base with the right hand before moving 3 m laterally back to cone B and touching its base. Finally, they moved 5 m backward as quickly as possible to cross line A (Fig. 2B). The fastest time (s) across two trials was retained for analysis.

3) Speed-endurance test. The test was conducted according to Marszałek et al. [19]. Participants started from a seated position behind the starting line at cone A and moved back and forth as quickly as possible between cone A and cones B, C, D, E, F, and G in sequence (Fig. 2C). They touched the base of each cone before returning to cone A and proceeding to the next cone. The fastest time (s) across two trials was retained for analysis. Completion times for all movement tests were recorded using wireless infrared timing gates (SmartSpeed; Fusion Sport, Coopers Plains, Australia) positioned at the respective start and finish lines.

Statistical analysis

All statistical analyses were performed using R software, version 4.4.2 (R Foundation for Statistical Computing, Vienna, Austria). Continuous-variable distributions were assessed using the Shapiro–Wilk test and visual inspection of quantile–quantile (Q–Q) plots. Data are presented as mean $\pm$ standard deviation. Differences between male and female participants were examined using Welch’s independent-samples *t*-tests, and between-sex effect sizes were expressed as Hedges’ *g* with 95% confidence intervals. Absolute Hedges’ *g* values of 0.20, 0.50, and 0.80 were interpreted as small, medium, and large, respectively, according to Cohen’s conventional thresholds [48]. Pearson’s correlation coefficients (*r*) with 95% confidence intervals were calculated to examine the associations between spike velocity and the anthropometric and physical performance variables. Based on Schober et al. [49], absolute correlation coefficients were interpreted as negligible (< 0.10), weak (0.10–0.39), moderate (0.40–0.69), strong (0.70–0.89), or very strong (≥ 0.90). An exploratory multiple linear regression analysis was performed using four predictors representing anthropometry, anaerobic performance, upper-body strength and power, and trunk function. One representative variable from each domain was selected based on theoretical relevance, movement specificity, a statistically significant false discovery rate (FDR)-adjusted correlation with spike velocity, and avoidance of redundant measures. Unstandardized regression coefficients (*B*) with 95% confidence intervals, standardized regression coefficients (β), R^2 , adjusted R^2 , and the overall *F* statistic were reported. Multicollinearity and model assumptions were assessed using variance inflation factors and residual diagnostics. Statistical significance was set at $p < 0.05$;

Benjamini–Hochberg-adjusted p values < 0.05 were considered statistically significant for the correlation analyses.

Results

Between-sex comparisons

Table 1 summarizes the between-sex comparisons for spike velocity, anthropometric characteristics, and physical performance variables. Male players achieved a higher spike velocity than female players (67.22 ± 6.74 vs. 51.51 ± 6.04 km/h; Hedges' $g = 2.38$ [1.43, 3.30], $p < 0.001$). Male players also had higher BMI, sitting height, seated vertical grip reach, and hand span (all $p \leq 0.020$), with large between-sex effects (Hedges' $g = 0.86$ – 2.41). PP, MP, rPP, and FI were also higher in male players (all $p \leq 0.038$), with medium-to-large effects (Hedges' $g = 0.75$ – 2.42), whereas rMP did not differ significantly between sexes ($p = 0.145$). For upper-body strength and power, male players achieved higher handgrip strength, 1RM bench press, and seated medicine-ball chest-pass distances (all $p < 0.001$), with large effects (Hedges' $g = 1.99$ – 3.76). Male players also achieved a greater seated rotational medicine-ball throw distance (Hedges' $g = 1.86$ [1.00, 2.69], $p < 0.001$). In contrast, female players completed more repetitions in the back-extension endurance test (50.43 ± 5.57 vs. 44.56 ± 6.69 repetitions; Hedges' $g = -0.92$ [-1.65, -0.18], $p = 0.014$). Curl-up performance did not differ significantly between sexes ($p = 0.283$). Male players recorded shorter completion times in the 5-m forward sprint (1.95 ± 0.29 vs. 2.33 ± 0.36 s; Hedges' $g = -1.16$ [-1.91, -0.39], $p = 0.004$) and 5-m backward sprint (1.85 ± 0.40 vs. 2.39 ± 0.53 s; Hedges' $g = -1.13$ [-1.88, -0.36], $p = 0.005$). No significant between-sex differences were observed for the modified agility T-test ($p = 0.157$) or speed-endurance test ($p = 0.189$).

Table 1
Between-sex comparisons of spike velocity and physical characteristics

Variables	Male (n = 16) Mean $\pm$ SD	Female (n = 14) Mean $\pm$ SD	Hedges' g [95% CI]	p
Spike velocity (km/h)	67.22 $\pm$ 6.74	51.51 $\pm$ 6.04	2.38 [1.43, 3.30]	< 0.001
Anthropometric characteristics				
Sitting height (cm)	97.10 $\pm$ 3.97	89.51 $\pm$ 2.31	2.23 [1.31, 3.13]	< 0.001
Seated vertical grip reach (cm)	152.30 $\pm$ 6.91	136.01 $\pm$ 6.15	2.41 [1.46, 3.34]	< 0.001
Hand span (cm)	19.52 $\pm$ 1.28	18.06 $\pm$ 1.07	1.20 [0.43, 1.96]	0.002
BMI (kg/m ²)	23.38 $\pm$ 3.62	20.81 $\pm$ 1.79	0.86 [0.12, 1.58]	0.020
Anaerobic performance				
PP (W)	575.00 $\pm$ 116.23	334.64 $\pm$ 67.45	2.42 [1.47, 3.35]	< 0.001
MP (W)	330.07 $\pm$ 75.67	217.58 $\pm$ 30.80	1.85 [0.99, 2.68]	< 0.001
rPP (W·kg ⁻¹)	7.41 $\pm$ 1.91	5.78 $\pm$ 1.18	0.98 [0.23, 1.72]	0.009
rMP (W·kg ⁻¹)	4.24 $\pm$ 1.09	3.76 $\pm$ 0.60	0.52 [- 0.20, 1.22]	0.145
FI (W·s ⁻¹)	12.74 $\pm$ 8.12	7.75 $\pm$ 3.67	0.75 [0.02, 1.47]	0.038
Upper-body strength and power				
Handgrip strength (kg)	49.02 $\pm$ 5.81	31.59 $\pm$ 2.80	3.64 [2.45, 4.80]	< 0.001
1RM bench press (kg)	93.31 $\pm$ 12.96	53.75 $\pm$ 5.61	3.76 [2.55, 4.95]	< 0.001
Seated medicine-ball chest pass (cm)	621.19 $\pm$ 49.16	534.64 $\pm$ 32.66	1.99 [1.11, 2.85]	< 0.001
Between-sex differences were tested using Welch's independent-samples t-tests. Hedges' g is the standardized mean difference between male and female participants; positive values indicate higher values in male participants. PP, peak power; MP, mean power; rPP, relative peak power; rMP, relative mean power; FI, fatigue index; 1RM, one-repetition maximum.				

Variables	Male (n = 16) Mean ± SD	Female (n = 14) Mean ± SD	Hedges' g [95% CI]	p
Trunk function				
Curl-up test (repetitions)	36.25 ± 4.64	38.07 ± 4.46	-0.39 [- 1.09, 0.32]	0.283
Back-extension endurance test (repetitions)	44.56 ± 6.69	50.43 ± 5.57	-0.92 [- 1.65, - 0.18]	0.014
Seated rotational medicine-ball throw (cm)	771.78 ± 103.92	604.64 ± 63.72	1.86 [1.00, 2.69]	< 0.001
Sport-specific movement performance				
5-m forward sprint test (s)	1.95 ± 0.29	2.33 ± 0.36	-1.16 [- 1.91, - 0.39]	0.004
5-m backward sprint test (s)	1.85 ± 0.40	2.39 ± 0.53	-1.13 [- 1.88, - 0.36]	0.005
Modified agility T-test (s)	8.99 ± 1.31	9.59 ± 0.94	-0.51 [- 1.21, 0.21]	0.157
Speed-endurance test (s)	21.22 ± 1.61	22.41 ± 2.88	-0.50 [- 1.21, 0.21]	0.189
Between-sex differences were tested using Welch's independent-samples t-tests. Hedges' g is the standardized mean difference between male and female participants; positive values indicate higher values in male participants. PP, peak power; MP, mean power; rPP, relative peak power; rMP, relative mean power; FI, fatigue index; 1RM, one-repetition maximum.				

Correlations with spike velocity

Table 2 presents descriptive statistics for the total sample and correlations between spike velocity and the anthropometric and physical performance variables. Mean spike velocity was 59.89 ± 10.17 km/h. After Benjamini–Hochberg correction, strong positive correlations with spike velocity were observed for seated vertical grip reach ($r = 0.80$ [0.62, 0.90], adjusted $p < 0.001$), sitting height ($r = 0.76$ [0.55, 0.88], adjusted $p < 0.001$), handgrip strength ($r = 0.75$ [0.53, 0.87], adjusted $p < 0.001$), 1RM bench press ($r = 0.74$ [0.53, 0.87], adjusted $p < 0.001$), and seated medicine-ball chest-pass distance ($r = 0.70$ [0.45, 0.85], adjusted $p < 0.001$). Moderate positive correlations were found for hand span ($r = 0.69$ [0.44, 0.84], adjusted $p < 0.001$), seated rotational medicine-ball throw distance ($r = 0.65$ [0.38, 0.82], adjusted $p < 0.001$), PP ($r = 0.51$ [0.19, 0.74], adjusted $p = 0.009$), and MP ($r = 0.51$ [0.18, 0.73], adjusted $p = 0.009$). BMI, back-extension endurance, and 5-m backward sprint time were associated with spike velocity before correction, but these associations did not remain significant after correction (adjusted $p = 0.051$, 0.058, and 0.052, respectively). No significant FDR-adjusted correlations were found for rPP, rMP, FI, curl-up performance, 5-m forward sprint time, modified agility T-test time, or speed-endurance test time.

Table 2
Descriptive statistics and correlations with spike velocity

Variables	Total (n = 30) Mean $\pm$ SD	Pearson's r [95% CI]	p	BH-adjusted p
Spike velocity (km/h)	59.89 $\pm$ 10.17	—	—	—
Anthropometric characteristics				
Sitting height (cm)	93.56 $\pm$ 5.04	0.76 [0.55, 0.88]	< 0.001	< 0.001
Seated vertical grip reach (cm)	144.70 $\pm$ 10.48	0.80 [0.62, 0.90]	< 0.001	< 0.001
Hand span (cm)	18.84 $\pm$ 1.38	0.69 [0.44, 0.84]	< 0.001	< 0.001
BMI (kg/m ²)	22.18 $\pm$ 3.15	0.40 [0.05, 0.67]	0.027	0.051
Anaerobic performance				
PP (W)	462.84 $\pm$ 154.60	0.51 [0.19, 0.74]	0.004	0.009
MP (W)	277.58 $\pm$ 81.52	0.51 [0.18, 0.73]	0.004	0.009
rPP (W·kg ⁻¹)	6.65 $\pm$ 1.79	0.10 [– 0.27, 0.45]	0.595	0.665
rMP (W·kg ⁻¹)	4.02 $\pm$ 0.91	0.00 [– 0.36, 0.36]	0.995	0.995
FI (W·s ⁻¹)	10.41 $\pm$ 6.82	0.31 [– 0.06, 0.60]	0.099	0.145
Upper-body strength and power				
Handgrip strength (kg)	40.88 $\pm$ 9.96	0.75 [0.53, 0.87]	< 0.001	< 0.001
1RM bench press (kg)	74.85 $\pm$ 22.45	0.74 [0.53, 0.87]	< 0.001	< 0.001
Seated medicine-ball chest pass (cm)	580.80 $\pm$ 60.47	0.70 [0.45, 0.85]	< 0.001	< 0.001
Trunk function				
Curl-up test (repetitions)	37.10 $\pm$ 4.57	–0.29 [– 0.59, 0.08]	0.117	0.159
Back-extension endurance test (repetitions)	47.30 $\pm$ 6.78	–0.38 [– 0.65, – 0.03]	0.037	0.058
Pearson's correlation coefficients (r) and 95% confidence intervals describe associations with spike velocity. The Benjamini–Hochberg procedure was used to adjust p values for multiple correlation tests. PP, peak power; MP, mean power; rPP, relative peak power; rMP, relative mean power; FI, fatigue index; 1RM, one-repetition maximum.				

Variables	Total (n = 30) Mean $\pm$ SD	Pearson's r [95% CI]	p	BH-adjusted p
Seated rotational medicine-ball throw (cm)	693.78 $\pm$ 120.83	0.65 [0.38, 0.82]	< 0.001	< 0.001
Sport-specific movement performance				
5-m forward sprint test (s)	2.13 $\pm$ 0.37	-0.24 [- 0.56, 0.13]	0.194	0.245
5-m backward sprint test (s)	2.10 $\pm$ 0.54	-0.40 [- 0.66, - 0.04]	0.030	0.052
Modified agility T-test (s)	9.27 $\pm$ 1.18	-0.04 [- 0.40, 0.32]	0.819	0.864
Speed-endurance test (s)	21.77 $\pm$ 2.33	-0.13 [- 0.47, 0.24]	0.503	0.597
Pearson's correlation coefficients (r) and 95% confidence intervals describe associations with spike velocity. The Benjamini–Hochberg procedure was used to adjust p values for multiple correlation tests. PP, peak power; MP, mean power; rPP, relative peak power; rMP, relative mean power; FI, fatigue index; 1RM, one-repetition maximum.				

Exploratory multiple linear regression analysis

Seated vertical grip reach, PP, 1RM bench press, and seated rotational medicine-ball throw were entered simultaneously into the exploratory multiple linear regression model (Fig. 3). The model was statistically significant and explained 77.3% of the variance in spike velocity ($R^2 = 0.773$, adjusted $R^2 = 0.736$, $F(4, 25) = 21.24$, $p < 0.001$) (Table 3). After adjustment for the other predictors, seated vertical grip reach was positively associated with spike velocity ($B = 0.647$, 95% CI [0.355, 0.938], $\beta = 0.667$, $t = 4.57$, $p < 0.001$). PP showed a negative coefficient ($B = -0.025$, 95% CI [- 0.046, - 0.003], $\beta = -0.375$, $t = -2.40$, $p = 0.024$), whereas 1RM bench press showed a positive coefficient ($B = 0.211$, 95% CI [0.042, 0.381], $\beta = 0.467$, $t = 2.57$, $p = 0.016$). Seated rotational medicine-ball throw was not independently associated with spike velocity ($B = 0.011$, 95% CI [- 0.014, 0.035], $\beta = 0.128$, $t = 0.90$, $p = 0.376$). Variance inflation factors ranged from 2.22 to 3.62, indicating no problematic multicollinearity. Residual diagnostics showed no marked deviations from normality or homoscedasticity; however, one potentially influential observation was identified and should be considered when interpreting the model.

Table 3
Exploratory multiple linear regression model for spike velocity

Predictor	B [95% CI]	SE	β	t	p	VIF
Seated vertical grip reach	0.647 [0.355, 0.938]	0.142	0.667	4.57	< 0.001	2.343
PP	-0.025 [- 0.046, - 0.003]	0.010	-0.375	-2.40	0.024	2.689
1RM bench press	0.211 [0.042, 0.381]	0.082	0.467	2.57	0.016	3.622
Seated rotational medicine-ball throw	0.011 [- 0.014, 0.035]	0.012	0.128	0.90	0.376	2.222
Overall model: $R^2 = 0.773$, adjusted $R^2 = 0.736$, $F(4, 25) = 21.24$, $p < 0.001$. B, unstandardized regression coefficient; β , standardized regression coefficient; CI, confidence interval; SE, standard error; VIF, variance inflation factor; PP, peak power; 1RM, one-repetition maximum.						

Discussion

This study examined the associations between spike velocity and a comprehensive range of anthropometric and physical performance characteristics in elite sitting volleyball players. Male players produced markedly greater spike velocity than female players. In the pooled sample, seated vertical grip reach, sitting height, handgrip strength, 1RM bench press, and seated medicine-ball chest-pass distance showed strong correlations with spike velocity that remained significant after FDR correction. Hand span, seated rotational medicine-ball throw distance, PP, and MP showed moderate positive correlations. In contrast, rPP, rMP, FI, trunk endurance, and most sport-specific movement tests were not significantly associated with spike velocity after correction. The exploratory model explained 77.3% of the variance in spike velocity and yielded positive coefficients for seated vertical grip reach and 1RM bench press. The negative PP coefficient and nonsignificant rotational-throw coefficient warrant cautious interpretation. Overall, the findings suggest that seated reach and general upper-body force-generating capacity are closely related to maximal spike velocity, whereas the contributions of general anaerobic and movement capacities appear more indirect and task dependent.

Sex-related differences and interpretation of pooled associations

The large sex-related difference in spike velocity was accompanied by marked differences in seated anthropometry, absolute anaerobic power, upper-body strength, medicine-ball throwing performance, and short-distance movement speed. This pattern is consistent with previous sitting volleyball studies reporting sex-related differences in strength-, power-, and speed-oriented tests [3] and distinct physical profiles between national- and league-level players [4]. In standing volleyball, elite male and female players also differ in spike-jump mechanics and the distribution of arm-swing techniques, reflecting

differences in anthropometry, force production, and movement strategy [12, 50]. This degree of separation by sex is important when interpreting the pooled analysis. Because sex was strongly related to both spike velocity and many explanatory variables, some pooled correlations may partly reflect between-sex differences rather than equally strong within-sex relationships. The results should therefore be interpreted as associations across a mixed-sex elite sample. Larger studies should examine within-sex correlations and use sex-adjusted or sex-stratified multivariable models.

Seated reach as the primary anthropometric correlate

Among the anthropometric variables, seated vertical grip reach showed the strongest association with spike velocity and retained a positive coefficient in the exploratory model. Sitting height and hand span were also positively correlated with spike velocity. Seated vertical grip reach is a composite measure influenced by sitting height, upper-limb length, and overhead reach; greater reach may allow a higher contact position and a longer effective acceleration path before impact. This interpretation is consistent with sitting volleyball serve research showing that vertical reach contributed to ball-impact height and that impact height contributed to serve velocity [20], as well as earlier associations among reach measures, spike-position height, field-test performance, and game performance [2, 19]. Tennis research further indicates that height, sitting height, arm dimensions, and contact height are associated with serve velocity in several populations [21–25]. Nevertheless, anthropometric associations are not consistent across sports or samples and may be mediated by technique, sex, maturation, and body composition. Because contact height, hand velocity, and upper-limb segment lengths were not measured directly, the present findings identify seated vertical grip reach as a correlate rather than establish a specific biomechanical mechanism. The moderate association with hand span may likewise reflect overall body size or more favorable hand–ball interaction, but direct assessment of impact area and contact mechanics is needed.

Upper-body strength and anaerobic power

The strong positive associations of handgrip strength, 1RM bench press, and seated medicine-ball chest-pass distance with spike velocity indicate that athletes with greater general upper-body force- and power-generating capacities tended to produce faster spikes. This finding agrees with standing volleyball evidence linking spike velocity to shoulder and elbow concentric strength and to force–velocity characteristics derived from ballistic upper-body testing [9, 11]. Comparable findings in team handball show that throwing velocity is related to 1RM bench press, peak power, bar velocity, fat-free mass, and upper-body power, supporting a broader relationship between force-generating capacity and high-velocity overarm actions [28, 29]. Beach-volleyball research has likewise associated serve velocity with shoulder strength characteristics [27]. In the present exploratory model, 1RM bench press retained a positive coefficient, suggesting that maximal upper-body strength may provide a force reserve for the spike. However, the bench press is a relatively slow, bilateral horizontal-pushing task, and handgrip strength may primarily indicate overall upper-extremity development. Longitudinal volleyball evidence showing that improvements in general strength and medicine-ball performance do not necessarily translate into faster spikes further highlights the limited task specificity of these assessments [30].

General strength and power tests should therefore be regarded as complementary indicators rather than substitutes for direct, technique-specific assessment.

Absolute PP and MP were moderately associated with spike velocity, whereas rPP, rMP, and FI were not significant after FDR correction. Previous sitting volleyball research has shown that arm-crank WAnT outcomes are related to sprinting, agility, speed endurance, medicine-ball chest-pass performance, and selected game-performance indicators [19]. The present findings extend this evidence by suggesting that absolute upper-body anaerobic power is also related to maximal spike velocity at the bivariate level. The absence of corresponding associations for relative power suggests that the PP and MP relationships may partly reflect body size, active muscle mass, or sex-related differences rather than power expressed per kilogram of total body mass. The arm-crank WAnT and spike also differ substantially: the former is a bilateral, cyclical, 30-s task, whereas the latter is a brief, unilateral, noncyclical action requiring precise segmental timing. Importantly, PP was positively correlated with spike velocity in the bivariate analysis but had a negative coefficient after the other predictors were entered. This reversal should not be interpreted as evidence that greater PP is detrimental. It is more plausibly attributable to shared predictor variance, sex-related clustering, coefficient suppression, the small sample, and the potentially influential observation identified in the diagnostic analysis. Replication in larger, sex-adjusted samples is required before physiological meaning is assigned to this coefficient.

Trunk function and sport-specific movement performance

The associations with spike velocity differed according to the trunk test. Seated rotational medicine-ball throw distance showed a moderate positive correlation, whereas curl-up performance was unrelated and back-extension endurance was not significant after FDR correction. The rotational throw requires rapid trunk rotation coordinated with arm movement and therefore shares more mechanical features with an overhand strike than repetition-based endurance tests. Side and seated medicine-ball throw studies have linked rotational throwing performance to general physical capacities, mobility, and throwing velocity [31, 32], whereas direct dynamometry research has shown an association between trunk-rotator strength and rotational medicine-ball throw performance [33]. More broadly, overarm-throwing research indicates that pelvis and upper-torso orientation, rotational velocity, and sequencing are related to ball velocity and upper-extremity mechanics [17, 18]. Nevertheless, the rotational throw did not contribute independently in the exploratory model, suggesting overlap with seated reach, body dimensions, upper-body strength, or sex. The null findings for curl-up and back-extension endurance likely reflect a mismatch between repeated muscular endurance and the brief, explosive, and technically coordinated trunk action required during a maximal spike; they do not imply that trunk endurance is unimportant for postural control or repeated performance during competition.

Sport-specific movement measures were generally not associated with spike velocity after FDR correction. Although male players were faster than female players in the 5-m forward and backward sprint tests, neither sprint test, the modified agility T-test, nor the speed-endurance test showed a significant association with spike velocity after correction. Previous studies have demonstrated relationships between WAnT outcomes and sport-specific movement tests [19], between field fitness

and coach-rated sitting volleyball performance [34], and between anthropometric and strength characteristics and floor-based sprint performance [5]. Physical-test profiles also differ between national- and league-level players, indicating that these tests capture meaningful aspects of overall performance readiness [4]. However, the present spike test was conducted under controlled conditions with standardized sets, a predefined target zone, and adequate recovery. Once an athlete was positioned to attack, floor-movement speed may have contributed little to the velocity transferred to the ball. Coaches should therefore regard field-movement tests and direct spike-velocity assessment as complementary rather than interchangeable: movement tests assess the capacity to reach and repeatedly regain effective positions, whereas radar testing assesses ball acceleration during the striking action itself.

Limitations and future directions

Several limitations warrant consideration. First, the cross-sectional design precludes causal inference; the observed associations do not establish that increasing strength, anaerobic power, or rotational throwing performance will improve spike velocity. Second, although the sample was substantial for an elite national-team sitting volleyball study, 30 participants were insufficient for stable sex-specific models and allowed only a limited number of predictors. The exploratory regression model was informed by the bivariate analysis, may provide an optimistic estimate of explained variance, and contained one potentially influential observation. Sex was not included in the reported model despite the large sex-related differences; future studies should conduct sex-adjusted sensitivity analyses. Third, 27 participants were classified as VS1 and only three as VS2, precluding meaningful analysis by sport class or impairment type. Fourth, ball-contact height, hand velocity, trunk angular velocity, shoulder and elbow kinematics, set trajectory, and impact mechanics were not measured. These variables may help distinguish anthropometric advantage from technical and biomechanical mechanisms. Finally, several field tests were adapted for sitting volleyball, and their reliability and validity in mixed-sex elite samples require further investigation. Future multicenter studies should combine direct kinematic and kinetic measures with physical testing, include larger sex- and classification-specific samples, and use longitudinal designs to determine whether changes in physical capacity are accompanied by changes in spike velocity.

Conclusions

In the pooled sample of elite sitting volleyball players, spike velocity was most strongly associated with seated anthropometric dimensions, upper-body strength, and seated medicine-ball chest-pass performance. Hand span, seated rotational medicine-ball throw performance, and absolute anaerobic power showed moderate positive associations. In contrast, relative WAnT outcomes, trunk endurance, and most sport-specific movement tests were not significantly associated with maximal spike velocity after FDR correction. In the exploratory multivariable model, seated vertical grip reach and 1RM bench press had positive coefficients; however, the negative PP coefficient and high proportion of explained variance should be interpreted cautiously because of shared predictor variance, the mixed-sex sample,

and one potentially influential observation. These findings support the combined use of seated anthropometry, upper-body strength assessment, rotational throwing assessment, and direct spike-velocity testing for athlete profiling while emphasizing that the reported relationships are associative rather than causal.

Abbreviations

1RM

one-repetition maximum

BH

Benjamini–Hochberg

BMI

body mass index

CI

confidence interval

FDR

false discovery rate

FI

fatigue index

ISAK

International Society for the Advancement of Kinanthropometry

MP

mean power

NSCA

National Strength and Conditioning Association

PP

peak power

Q–Q

quantile–quantile

rMP

relative mean power

rPP

relative peak power

SD

standard deviation

SE

standard error

VIF

variance inflation factor

VS1 and VS2

World ParaVolley sport classes

WAnT

Wingate Anaerobic Test.

Declarations

Ethics approval and consent to participate

The study was approved by the Beijing Sport University Human Participants Review Board (approval no. 2025195H) and conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent before participation.

Consent for publication

Written informed consent was obtained from all participants for the publication of their identifiable images and/or personal details.

Competing interests

The authors declare that they have no competing interests.

Authors' information

Not applicable.

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Author Contribution

S.S. and J.Y. contributed to the conception and design of the study. S.S. and M.R. contributed to data collection and data extraction and drafted the manuscript. J.Y. critically revised the manuscript for important intellectual content. All authors approved the final manuscript and agree to be accountable for the work.

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Data Availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

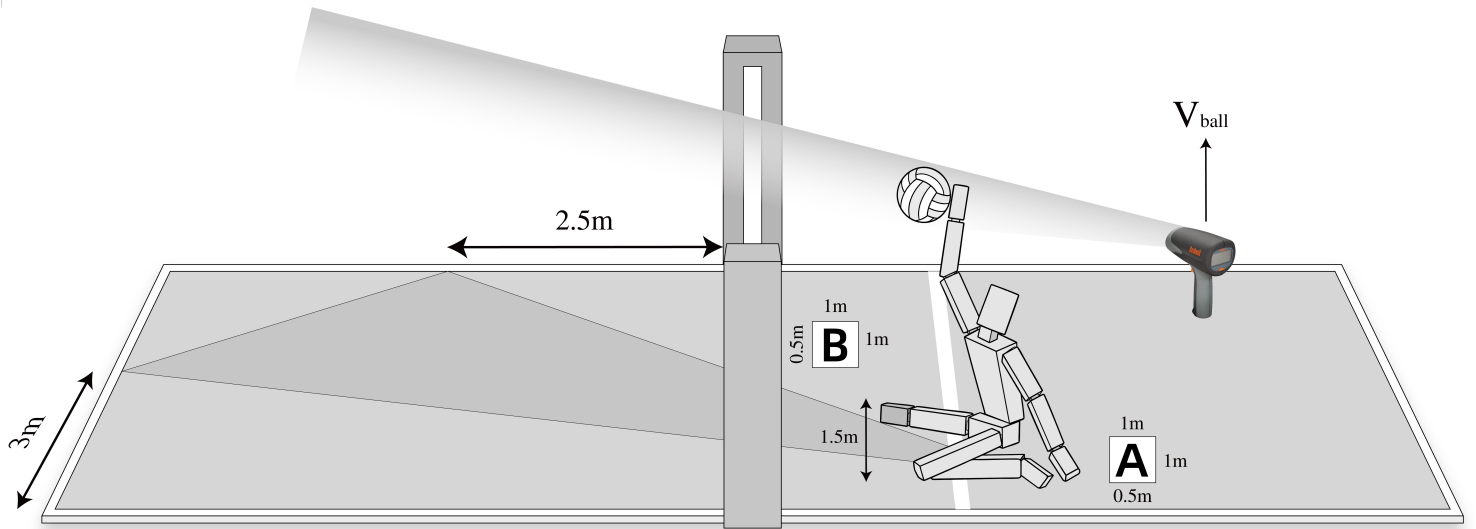


Figure 1

Experimental setup for the spike velocity test. (A) Starting zone of the spiker, 0.50 m from the left side and 2.50 m from the center line; (B) starting zone of the setter, 3.50 m from the left side and 0.50 m from the center line.

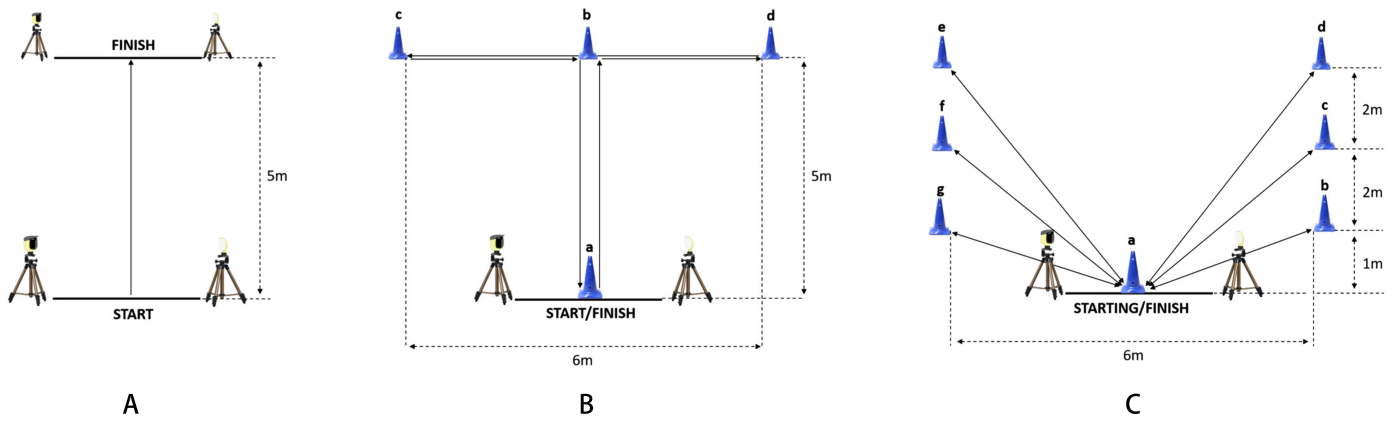


Figure 2

Experimental setups for sport-specific movement tests. (A) Layout for the 5-m forward and backward sprint tests; (B) layout for the modified agility T-test; (C) layout for the speed-endurance test.

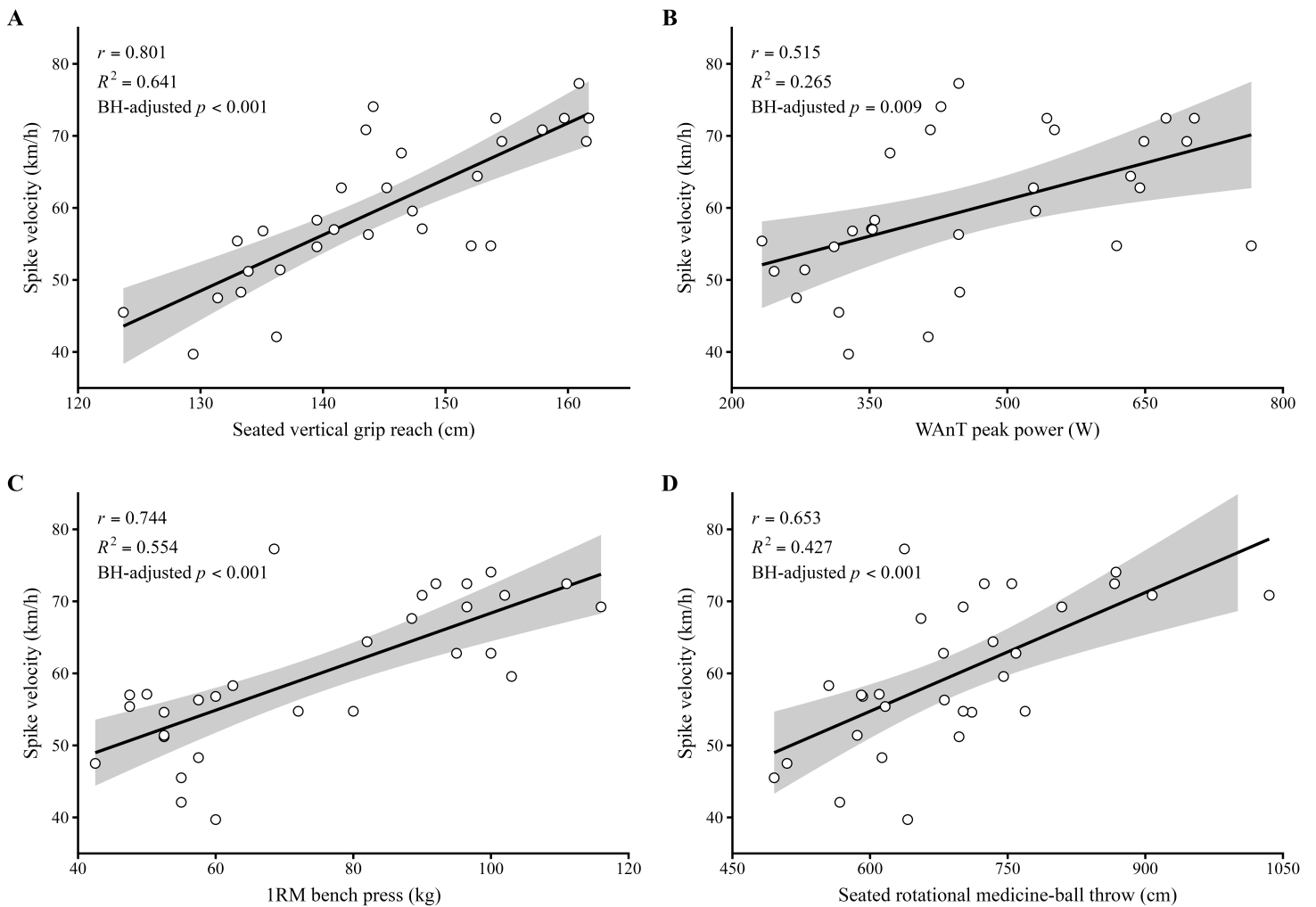


Figure 3

Bivariate associations between spike velocity and regression-model predictors. (A) Seated vertical grip reach; (B) Wingate peak power; (C) one-repetition maximum bench press; and (D) seated rotational medicine-ball throw. Solid lines represent pooled linear regression fits, and shaded areas represent 95% confidence intervals. Pearson's correlation coefficients and Benjamini–Hochberg-adjusted p values are displayed in each panel.