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# Ciencia y Deporte



*Original article*

***Probabilistic robustness of the female jump float serve: Monte Carlo simulation with net regulation criteria and uncertainty propagation***

*[Robustez probabilística del saque flotante con salto femenino: simulación Monte Carlo con criterio reglamentario de red y propagación de incertidumbre]*

*[Robustez probabilística do saque flutuante com salto no voleibol feminino: simulação de Monte Carlo com critério regulamentar de rede e propagação de incerteza]*

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**ABSTRACT**

**Introduction:** the jump float serve dominates elite women's volleyball, and its outcome depends on execution variability and fluctuating aerodynamic forces.

**Objective:** to estimate, through modelling, which release speed-angle combinations increase the probability of a rule-compliant serve without leaving the repertoire observed in elite players.

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**Materials and methods:** a computational study using a three-dimensional flight model (gravity, speed-dependent drag of the V200W ball and Ornstein-Uhlenbeck perturbations), informed by player-level data from six indoor players (92 serves). A serve was valid when it crossed the crossing space, with or without net contact (FIVB Rule 10.2), and first touched the floor inside the court; contact with the net top band was simulated as an impact. We used 50,000 trajectories per configuration with common random numbers, an extended 14–20 m/s  $\times$  6–20° grid, an empirical  $\pm 2$  SD per-player domain, a hierarchical per-player bootstrap, 21 epistemic scenarios and Morris screening of 13 factors. Code and data are openly available.

**Results:** at baseline (17.79 m/s; 9.87°) the model-estimated valid-serve probability was 62.55% (95% Monte Carlo CI: 62.12–62.97%), consistent with the source's observed rate (63.9%). Without an empirical constraint the maximum moved to the grid edge. Within the empirical domain, the candidate 16.2 m/s and 14.5° reached 87.25% (86.95–87.54%), with 67.76% deep landings. Parameter uncertainty of the source widened the interval to 83.1–91.4%. The gain over baseline was positive in all 21 scenarios (17.6–26.8 percentage points), although its absolute level ranged from 57.4% to 93.3%. **Conclusions:** a somewhat lower speed and a higher angle than the observed mean increase the simulated probability of a valid serve. The proposed configuration depends on the admitted domain and has not been validated in the field; it should be treated as a hypothesis for an individualized prospective protocol.

**Keywords:** Volleyball; Float serve; Biomechanics; Aerodynamics; Monte Carlo simulation; Uncertainty analysis.

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## RESUMEN

**Introducción:** el saque flotante con salto predomina en el voleibol femenino de élite y su resultado depende de la variabilidad de ejecución y de fuerzas aerodinámicas fluctuantes.

**Objetivo:** estimar, mediante un modelo, qué combinaciones de velocidad y ángulo de salida aumentan la probabilidad de saque reglamentariamente válido sin abandonar el repertorio observado en jugadoras de élite.

**Materiales y métodos:** estudio computacional con un modelo tridimensional de vuelo (gravedad, arrastre dependiente de la velocidad del balón V200W y perturbaciones de Ornstein-Uhlenbeck), alimentado con los datos por jugadora de seis voleibolistas indoor (92 saques). El balón se consideró válido si cruzaba el espacio de paso, con o sin contacto con la red (Regla FIVB 10.2), y su primer contacto con el suelo ocurría dentro del campo; el contacto con la banda superior se simuló como un impacto. Se usaron 50 000 trayectorias por configuración con números aleatorios comunes, una malla ampliada de 14–20 m/s y 6–20°, un dominio empírico de  $\pm 2$  SD por jugadora, un bootstrap jerárquico por jugadora, 21 escenarios epistémicos y un cribado de Morris de 13 factores. El código y los datos son abiertos.

**Resultados:** en la línea base (17,79 m/s; 9,87°), la probabilidad estimada por el modelo de saque válido fue 62,55 % (IC Monte Carlo 95 %: 62,12–62,97 %), compatible con la tasa observada en la fuente (63,9 %). Sin restricción empírica, el máximo se desplazó al borde de la malla. Dentro del dominio empírico, la candidata 16,2 m/s y 14,5° alcanzó 87,25 % (86,95–87,54 %), con 67,76 % de aterrizajes profundos. La incertidumbre paramétrica de la fuente amplió el intervalo a 83,1–91,4 %. La mejora frente a la línea base fue positiva en los 21 escenarios (17,6–26,8 puntos porcentuales), aunque su nivel absoluto varió entre 57,4 y 93,3 %.

**Conclusiones:** una velocidad algo menor y un ángulo mayor que la media observada aumentan la probabilidad simulada de saque válido. La configuración propuesta depende del dominio admitido y no está validada en campo; debe tratarse como hipótesis para un protocolo prospectivo individualizado.

**Palabras clave:** voleibol; ataque flotante; biomecánica; aerodinámica; simulación Monte Carlo; análisis de incertidumbre.

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## RESUMO

**Introdução:** o saque flutuante com salto predomina no voleibol feminino de elite, e seu resultado depende da variabilidade na execução e de forças aerodinâmicas flutuantes.

**Objetivo:** estimar, por meio de um modelo, quais combinações de velocidade e ângulo de saída aumentam a probabilidade de um saque regulamentarmente válido, sem fugir do repertório observado em jogadoras de elite.

**Materiais e métodos:** estudo computacional utilizando um modelo tridimensional de trajetória (considerando gravidade, arrasto dependente da velocidade da bola V200W e perturbações de Ornstein-Uhlenbeck), alimentado com dados de seis jogadoras de voleibol de quadra (92 saques). Um saque foi considerado válido se a bola atravessasse o espaço de passagem — com ou sem toque na rede (Regra 10.2 da FIVB) — e tocasse o solo pela primeira vez dentro da quadra; o contato com a faixa superior da rede foi simulado como um impacto. Foram geradas 50.000 trajetórias para cada configuração, utilizando números aleatórios comuns, uma grade ampliada (velocidade: 14–20 m/s; ângulo: 6–20°), um domínio empírico de  $\pm 2$  desvios-padrão (DP) por jogadora, \*bootstrap\* hierárquico por jogadora, 21 cenários epistêmicos e uma análise de triagem de Morris com 13 fatores. O código e os dados estão disponíveis publicamente.

**Resultados:** na condição de referência (17,79 m/s; 9,87°), a probabilidade de um saque válido, estimada pelo modelo, foi de 62,55% (IC de Monte Carlo de 95%: 62,12–62,97%), valor compatível com a taxa observada na fonte (63,9%). Sem restrições empíricas, o ponto de probabilidade máxima deslocou-se para a borda da grade de análise. Dentro do domínio empírico, a configuração de 16,2 m/s e 14,5° alcançou 87,25% (86,95–87,54%), com 67,76% de aterrissagens profundas. A incerteza paramétrica da fonte ampliou o intervalo para 83,1–91,4%. A melhoria em relação à linha de base foi positiva em todos os 21 cenários (17,6–26,8 pontos percentuais), embora o valor absoluto tenha variado entre 57,4% e 93,3%.

**Conclusões:** uma velocidade ligeiramente menor e um ângulo maior do que a média observada aumentam a probabilidade simulada de um saque válido. A configuração proposta depende do domínio considerado e não foi validada em campo; deve ser tratada como uma hipótese para um protocolo prospectivo individualizado.

**Palavras-chave:** voleibol; saque flutuante; biomecânica; aerodinâmica; simulação de Monte Carlo; análise de incerteza.

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## INTRODUCTION

The serve is the only action in volleyball initiated without direct interference from the opponent and constitutes both a scoring opportunity and the first mechanism for disrupting the reception. Its evaluation is no longer limited to aces: it includes errors, the quality of the reception induced, the target zone, and the possibility of restricting the opponent's first attack. Analyses of international competitions show that the importance of the serve changes with gender, the context of the set, and the score; in women's volleyball, Giatsis (2023) and Wang (2025) describe the weight of the serve and the first attack in the Olympic Games and World Championships, while studies with male or mixed samples (Drikos *et al.*, 2025; Maneiro *et al.*, 2026) serve only as comparative context.

In women's volleyball, the jump float serve occupies a central position. Pawlik *et al.* (2024) analyzed more than fifty thousand serves and found that this technique represented approximately 86% of women's serves; Shen *et al.* (2026) reported a prevalence of 89.5% in elite women's volleyball. The technique combines a contained error with a trajectory that is difficult to anticipate, consistent with the technical nature of the women's game (Pawlik and Mroczek, 2023; Fatahi *et al.*, 2022).

The difficulty of the float serve has two sources of uncertainty. The first is biomechanical: no two players reproduce exactly the same speed, angle, and height of contact. The second is aerodynamic: the orientation of the panels and the airflow regime modify drag and transverse forces. Reiser *et al.* (2020) quantified launch conditions and trajectory deviations in actual float serves; Hong *et al.* (2020) and Tamaru *et al.* (2021) showed that the V200W ball exhibits drag transitions and fluctuating forces that depend on orientation; and Laios *et al.* (2026) documented flight deviations on the order of tens of

centimeters in standing float serves. A trajectory calculated with unique values can be physically correct and, at the same time, not representative of actual repeatability.

Sensors, computer vision, and machine learning have expanded the evaluation of the serve (Casimiro-Artés *et al.*, 2024; Salim *et al.*, 2024); biomechanical studies link the kinetic chain to arm speed (Liu *et al.*, 2024), and machine learning studies show that the organization of practice influences serve acquisition (Qu *et al.*, 2025). However, the integration of biomechanics, aerodynamics, and uncertainty into a probabilistic tool that complies with the rules and explicitly states which part of a recommendation comes from data and which from model assumptions remains limited.

This study does not seek a perfect trajectory. It distinguishes three levels of evidence: (i) probabilities conditional on a numerically verified model; (ii) its consistency with observed statistics from the source; and (iii) the stability of comparisons between configurations in the face of parameter and model uncertainty. The objective was to estimate which combinations of average speed and angle increase the probability of a valid serve according to FIVB Rule 10.2, within the repertoire observed in elite players, and to quantify how much of this conclusion depends on unobserved assumptions. It was proposed that the most robust configuration would not coincide with the observed mean, but that its exact location would be conditioned by the permitted execution domain.

## **MATERIALS AND METHODS**

### *Design*

*in silico* simulation design. The unit of analysis was a complete trajectory from the instant after hand-ball contact to the first contact with the ground. No participants were recruited, nor were personal data processed; the biomechanical parameters were derived from previously published results for each player. The flow is summarized in Figure 1.

The model, the seeds, the input data, and all intermediate results were deposited in an open repository (section 2.9) (Figure 1).

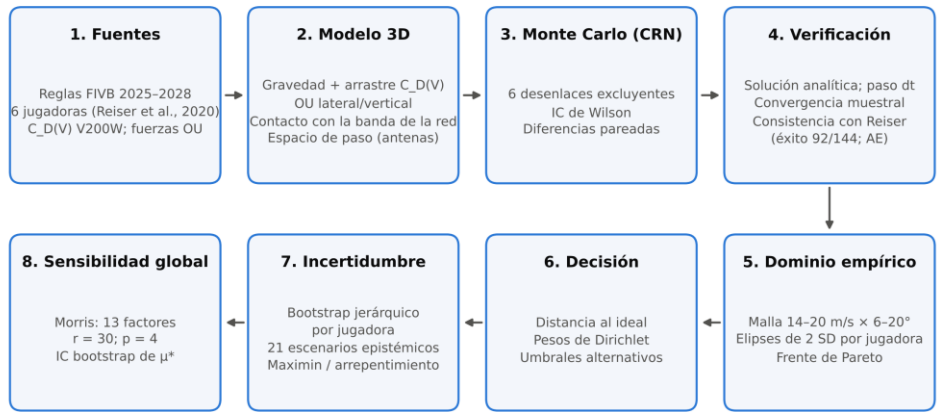


**Figure 1.** - Methodological flow. CRN: common random numbers; AE: anticipation error; OU: Ornstein- Uhlenbeck

*Geometry, rules and classification of outcomes*

A Cartesian coordinate system was used with its origin at the right corner of the server's baseline:  $x$  towards the receiver's court. (*red en  $x = 9\text{ m}$ ; campo receptor  $9 \leq x \leq 18\text{ m}$* ),  $y$  lateral ( $0 - 9\text{ m}$ )  $y$   $z$  vertical. The women's net was positioned at  $2.24\text{ m}$ . The angle  $\theta$  was measured along the horizontal (positive upwards) and the azimuth  $\psi$  with respect to the  $x$ -axis. According to Rule 8.3, the ball is "in" when any part of it touches the court, including the lines; operationally, the first contact with the ground was detected when the height of the center equaled the radius of the ball ( $r = 0,105\text{ m}$ ), and the point located below the center was evaluated, which is conservative with respect to the deformed footprint. According to Rules 8.4.4 and 10.1.1, the ball must cross the plane of the net within the crossing space limited by the antennas, located above the sidelines; this was required  $r + 0,005\text{ m} \leq y \leq 9 - r - 0,005\text{ m}$  at the crossing. According to Rule 10.2, the ball may touch the net as it crosses it (Fédération Internationale de Volleyball [FIVB], 2025).

Each trajectory was assigned to one of six mutually exclusive categories, with the total number of trajectories as the denominator: (1) valid without contact with the net; (2) valid after contact with the net; (3) does not clear the net (impact with the mesh or return to the sideline after touching the sideline); (4) outside the crossing space; (5) out at the back ( $x > 18$  m); and (6) out laterally.  $P(\text{válido}) = (1) + (2)$  This is the regulatory probability.  $P$  (geometric clearance without contact), i.e., crossing without contact within the crossing space regardless of landing, is reported separately, as is  $P$  (valid without contact) as a conservative lower bound. "Deep" is a subset of "valid" (valid landing with  $x \geq 15$  m);  $P(\text{deep})$  and  $P(\text{deep} \mid \text{valid})$  are reported.

### Biomechanical data

The initial conditions were derived from the six elite *indoor volleyball players* (all women; jump float serve; MVA200 ball) studied by Reiser *et al.* (2020), who analyzed 92 of 144 serves; the remaining 52 were balls into the net or out of bounds. Table 1 shows, for each player, the number of analyzable serves, the mean, and the intraplayer standard deviation (SD) of speed, angle, and height. The representative mean was weighted,  $n_i, \bar{x} = \sum \frac{n_i \bar{x}_i}{\sum n_i}$ , and technical variability was represented by the pooled intraplayer SD.

$s_p = \left[ \sum \frac{(n_i - 1) s_i^2}{\sum (n_i - 1)} \right]^{1/2}$  These yielded values of 17.79 m/s, 9.87°, and 2.557 m, with pooled SDs of 0.639 m/s, 2.148°, and 0.028 m. The standard deviation between player means (0.78 m/s; 0.83°; 0.059 m) was not combined with intra-player variation: it was addressed using individual scenarios and resampling by player (section 2.7). Because the source excluded missed serves, the published standard deviations may underestimate the variability of attempts; this truncation was assessed as an epistemic scenario. The source did not publish correlations between speed and angle; the nominal situation assumed independence (Table 1).

**Table 1.** - Input data per player (Reiser *et al.*, 2020) and individual results of the model

| Player                   | n         | $v \pm$<br>SD<br>(m/s)                       | $\theta \pm$<br>SD<br>(°)                   | $h$<br>(m)  | P(valid)<br>in its<br>mean (%) | The<br>candidate<br>gives (SD) | Individual<br>commitment<br>(m/s; °) | Individual<br>P(valid) (%) |
|--------------------------|-----------|----------------------------------------------|---------------------------------------------|-------------|--------------------------------|--------------------------------|--------------------------------------|----------------------------|
| 7                        | 15        | 17.77<br>$\pm 0.74$                          | 9.54 $\pm$<br>2.12                          | 2.44        | 55.1                           | 3.16                           | 16.9; 12.5                           | 73.9                       |
| 8                        | 22        | 16.79<br>$\pm 0.62$                          | 10.83<br>$\pm 2.49$                         | 2.56        | 70.5                           | 1.75                           | 16.1; 14.5                           | 86.4                       |
| 9                        | 14        | 19.06<br>$\pm 0.54$                          | 9.50 $\pm$<br>1.89                          | 2.58        | 40.0                           | 5.92                           | 18.2; 10.0                           | 59.2                       |
| 10                       | 12        | 18.62<br>$\pm 0.78$                          | 8.15 $\pm$<br>1.91                          | 2.65        | 52.9                           | 4.55                           | 17.5; 10.5                           | 70.6                       |
| 11                       | 18        | 17.73<br>$\pm 0.47$                          | 10.24<br>$\pm 1.61$                         | 2.57        | 71.8                           | 4.20                           | 17.0; 12.0                           | 84.1                       |
| 12                       | 11        | 17.39<br>$\pm 0.72$                          | 10.12<br>$\pm 2.70$                         | 2.56        | 61.8                           | 2.32                           | 16.4; 13.5                           | 79.7                       |
| <b>Grouped</b>           | <b>92</b> | <b>17.79</b><br><b><math>\pm 0.64</math></b> | <b>9.87 <math>\pm</math></b><br><b>2.15</b> | <b>2.56</b> | <b>62.5</b>                    | —                              | <b>16.2; 14.5</b>                    | <b>87.2</b>                |
| SD<br>between<br>players | —         | 0.78                                         | 0.83                                        | 0.06        | —                              | —                              | —                                    | —                          |

**Note.** n: analyzable serves (valid and without contact with the net, according to the source). SD: intraplayer standard deviation; height SDs were 0.02–0.03 m. “Pooled”: weighted mean by n intraplayer pooled SD; in that row, the last two columns correspond to the common candidate. d: Mahalanobis diagonal distance from the player's mean. Individual commitment: minimum distance to the ideal within their 2 SD ellipse (N = 2,000 per cell; final result with N = 20,000).

### Three-dimensional mechanical model

The movement of the center of the ball was described with:

$$\frac{dr}{dt} = v; \quad m \frac{dv}{dt} = m g + F_D + F_T$$

$$F_D = -\frac{1}{2} \rho A C_{D(v)} |v| v; \quad F_T = \frac{1}{2} \rho A |v|^2 (C_s e_s + C_l e_l)$$

Where  $e_s$  is the horizontal unit vector perpendicular to  $av$  y  $e_l = \hat{v} \times e_s$  the perpendicular vector  $av$  in the vertical plane. The MIKASA V200W ( $m = 0.27$  kg; circumference 0.66 m;  $A = 0.03466$  m<sup>2</sup>) and air at 20 ° C and 101,325 kPa ( $\rho = 1.204$  kg/m<sup>3</sup>) were adopted.  $C_{D(v)}$  Linear interpolation was performed on the digitized V200W curve (average of the two orientations; Tamaru *et al.*, 2021), with a digitization uncertainty of  $\pm 0.007$ ; the orientation curves and the MVA200 curve were used as scenarios. The contact

was positioned on the vertical of the baseline ( $x_0 = 0$ ), en  $y_0 = 3,5\text{ m}$ , center of the source's target corridor, with nominal azimuth  $\psi = 0$  and lateral error.  $\psi \sim N(0; 2^\circ)$  Integration used fourth-order Runge-Kutta with a fixed step of 0.001 s; The crossing of the network and the contact with the ground were interpolated within the step.

The net was modeled as a rigid horizontal edge  $z = 2,24\text{ m}$  (top band) on an absorbent mesh. If the ball touched the mesh below the edge, it was classified as "not clearing the net." If it touched the edge, an impulse was applied: the normal component was reversed with restitution  $e_n = 0,30$ , and the tangential component was multiplied by  $k_t = 0,60$ , a value corresponding to the non-slipping roll of a thin hollow sphere  $\frac{1}{1+\frac{2}{3}}$ . After contact, the trajectory continued with all forces and was classified by its first contact with the ground. Since there is no published calibration for a volleyball net band, the  $e_n$  y  $k_t$  parameters were treated as epistemic ( $e_n$ : 0,1 – 0,5;  $k_t$ : 0,4 – 0,9), and the lower bound that considers any contact a fault is reported.

#### *Aerodynamic disturbance*

stationary, zero-mean Ornstein- Uhlenbeck (OU) processes:

$$dC_j = -\left(\frac{C_j}{\tau}\right)dt + \sigma_j\left(\frac{2}{\tau}\right)^{\frac{1}{2}}dW_j, \quad j \in \{s, l\}$$

which were updated with their exact solution at each step. The amplitudes were derived from the force SDs measured at 15 m/s for the V200W (Hong *et al.*, 2020, Table 1; average of faces A and B): 0.845 N (lateral) and 0.825 N (vertical). Dividing these by  $\frac{1}{2} \rho (15\text{ m/s})^2 A$  of the model yielded the following.  $\sigma_s = 0,180$  y  $\sigma_l = 0,176$  This conversion corrects the previous version, which had used the 0.0314 m<sup>2</sup> area of the test. The force averages in fixed orientations were not transferred to the court axes because the model does not simulate the ball's attitude. The source does not publish a spectrum, so  $\tau = 0,045\text{ s}$  was treated as a nominal value without empirical calibration and explored over an order of magnitude (0.015–0.15 s). The components were assumed to be independent.

( $\rho_{sl} = 0$ ; *escenario*  $\rho_{sl} = 0,5$ ). Therefore, the OU process is a surrogate model of non-stationary forces, not a fluid dynamics simulation; its plausibility was tested against the observed deviations (section 2.6) (Table 2).

**Table 2.** Model parameters, nominal values, and explored ranges

| Cluster    | Parameter                            | Nominal value                                | Epistemic range                                   | Source or treatment                      |
|------------|--------------------------------------|----------------------------------------------|---------------------------------------------------|------------------------------------------|
| Regulation | Court; net; antennas                 | 18 × 9 m; 2.24 m; on the sidelines           | —                                                 | FIVB (2025), Rules 1, 2, 8 and 10        |
| Ball       | Mass; circumference; area            | 0.27 kg; 0.66 m; 0.03466 m <sup>2</sup>      | —                                                 | Nominal values V200W                     |
| Air        | Density $\rho$                       | 1,204 kg/m <sup>3</sup> (20 °C; 101,325 kPa) | 1.16–1.23                                         | 15–30 °C; 0–300 m above sea level        |
| Execution  | Media $v$ ; $\theta$ ; $h$           | 17.79 m/s; 9.87°; 2.557 m                    | $h$ : 2.44–2.65 m                                 | Reiser et al. (2020), Table 1            |
| Execution  | SD grouped $v$ ; $\theta$ ; $h$      | 0.639 m/s; 2.148°; 0.028 m                   | Scale 0.75–1.40                                   | Bootstrap; truncation                    |
| Execution  | $v$ - $\theta$ correlation           | 0                                            | -0.5 to 0.5                                       | Not published                            |
| Execution  | Contact $x_o$ ; $y_o$ ; error $\psi$ | 0 m; 3.5 m; SD 2°                            | $x_o$ : -1.0 to 0.5 m; $\psi$ : 0.5 – 4 °         | Target corridor of the source            |
| Drag       | $C_D(V)$                             | V200W, average of faces                      | ×0.85–1.15; translation ±2 m/s; faces A/B; MVA200 | Tamaru et al. (2021); Hong et al. (2020) |
| OU         | $\sigma_s$ ; $\sigma_l$              | 0.180; 0.176                                 | Scale 0.5–1.5                                     | Hong et al. (2020), Table 1              |
| OU         | $\tau$ ; $\rho_{sl}$                 | 0.045 s; 0                                   | 0.015–0.15 s (log); -0.5 to 0.5                   | Nominal value without published spectrum |
| Grid       | $e_n$ ; $k_t$                        | 0.30; 0.60                                   | 0.1–0.5; 0.4–0.9                                  | Hollow sphere rolling ( $k_t$ )          |
| Numeric    | Step; N                              | 0.001 s (RK4); 50,000                        | 0.00025–0.004 s                                   | Convergence (section 3.1)                |

**Note :** The ranks were used in the Morris screening and in the scenarios. OU: Ornstein- Uhlenbeck ;  
RK4: Runge- Kutta fourth order.

### Simulation, verification, and external consistency

Each configuration was evaluated with 50,000 trajectories; the mesh, scenarios, and Morri's screening used between 2,000 and 4,000. All configurations shared common

random numbers (CRNs): the same standard normals for the initial conditions and the same OU noise sequence, generated with a path- and step-indexed counter generator. Thus, differences between configurations were estimated pairwise, with 95% confidence intervals for the mean differences per trajectory. Proportions are accompanied by Wilson confidence intervals. These intervals quantify only the Monte Carlo error conditioned on the parameters; parameter and model uncertainty were evaluated separately (section 2.7).

Numerical verification included comparison with the analytical ballistic solution, time step convergence (0.004–0.00025 s), sample convergence, and reproduction of the deterministic record from the previous version. For external consistency, the same measurement procedure as Reiser *et al.* (2020) was applied to the simulated trajectories: sampling at 100 Hz up to [  $z < 0,7$  m value missing], parabolic drag-free fitting (their Eq. 1), and anticipation error (AE), calculated using the first 7 m of the trajectory and extrapolated to the 0.7 m plane. The analyzable strike rate (92/144), the vertical and horizontal AEs, and the adjusted parameters were compared. None of these statistics were used to set parameters, so the comparison is calibration-independent.

#### *Empirical domain, decision, and uncertainty*

899 cells with  $N = 4,000$  each  $D_k$  was explored. To avoid confusing the model optimum with a domain artifact, the empirical domain was defined  $14 - 20 \frac{m}{s} \left( \text{paso } 0,2 \frac{m}{s} \right) y 6 - 20^\circ \left( \text{paso } 0,5^\circ \right)$  as the set of cells whose diagonal Mahalanobis distance to the mean of at least one player is  $\leq k$ ,  $d_i = \left[ \left( \frac{v - \bar{v}_i}{s_v}, i \right)^2 + \left( \frac{\theta - \bar{\theta}_i}{s_\theta}, i \right)^2 \right]^{1/2}$ , con  $k = 2$  (approximately 86% of runs in a bivariate normal distribution) and  $k = 1 y 3$  as sensitivity. The four objectives were to maximize P(valid) and P(deep) and to minimize P (does not surpass the net) and P(bottom). On the non-dominated set  $D_2$ , each objective was normalized as and  $g_j = \frac{f_j - peor_j}{mejor_j - peor_j}$ , the candidate minimized the distance to the ideal.  $D = \left[ \sum w_j (1 - g_j)^2 \right]^{1/2}$  con  $w_j = \frac{1}{4}$ . Ties were resolved with  $N = 50,000$  in the 16 neighboring

cells  $(15,8 - 16,4 \frac{m}{s}; 13,5 - 15,0^\circ)$ . The sensitivity to weights was evaluated with 10,000 Dirichlet vectors  $(1, 1, 1, 1)$ , and the practical window was recalculated with alternative thresholds: margin of  $P(válido)$  de  $1 - 3 pp$ ;  $P(profundo) \geq 0,55 - 0,65$ ;  $P(red)$  y  $P(fondo) \leq 0,08 - 0,12$ .

Source uncertainty was propagated using a hierarchical bootstrap ( $B = 400$ ). In each replicate, the six players were  $N(\bar{x}_i, \frac{s_i^2}{n_i})$  resampled with replacement, followed by the mean of each player and their variance  $\frac{s_i^2 \chi_{\{n_i-1\}}^2}{n_i-1}$ . The weighted mean and pooled SDs were recalculated using these replicates, and the baseline and candidate were simulated. The analysis was then repeated using each player's own mean, SD, and height, seeking their best compromise within their 2 SD ellipse. Model uncertainty was assessed using 21 epistemic scenarios: the nominal scenario and 20 alternative scenarios: seven CD scenarios, five OU scenarios, two net contact scenarios, two contact position scenarios, two correlation scenarios, one truncation scenario, and one observation operator scenario. In each scenario, the  $D_2$  mesh and the paired difference between the candidate and the baseline were recalculated. In addition, the maximin cell and the minimum maximum regret cell were identified.

#### *Morris's global sensitivity*

Morris (1991) screening was limited to 13 epistemic parameters because mean speed and angle are decision variables, and their effect is described by the response surface. It was applied to the baseline and candidate, with  $r = 30$  trajectories,  $p = 4$  levels, and  $\Delta = \frac{2}{3}$  factors scaled to  $[0, 1]$  in the ranges of Table 2 ( $\tau$  on a logarithmic scale). The elementary effect was defined  $EE_i = \frac{[Y(x + \Delta e_i) - Y(x)]}{\Delta}$ , in probability units per full range traverse.  $\mu, \mu^*$  (*media de  $|EE|$* ),  $\sigma$  e IC 95 % de  $\mu^*$  por bootstrap de trayectorias ( $B = 1\,000$ ) Each evaluation used  $N = 4000$  with CRN and the 1991 seed. The speed-angle correlation enters as a joint distribution parameter, via Cholesky decomposition, and not as a correlated input; the shift of  $\mu^* C_D$  was parameterized as a multiplier and as a translation

of the drag crisis. Since  $\mu^*$  depends on the assigned range, comparisons between factors are conditional on those ranges.

### *Reproducibility*

The model was implemented in Python 3.13.17 (NumPy 2.5.3, SciPy 1.18.1, pandas 3.0.5, Numba 0.68.0 and Matplotlib 3.11.2), with main seed 20261026. The deposited package contains the simulation engine, the input data per player, the  $C_D$  digitized curves with their uncertainty, the parameters and their units, the seeds, the numbered scripts 01–12 that regenerate each table and figure, all the intermediate results, and a traceability table that links each figure in the manuscript to its source file and column.

## **RESULTS AND DISCUSSION**

### *Numerical verification and external consistency*

The error compared to the analytical solution without drag was [missing value  $\leq 3,1 \mu\text{m}$ ]. The deterministic landing point varied by 0.023 mm between steps of 0.004 and 0.00025 s, and  $P(\text{valid})$  varied by 0.26 pp between 0.002 and 0.0005 s, within the Monte Carlo error. ( $EE = 0,22 \text{ pp con } N = 50\,000$ ). The open reimplementation reproduced the deterministic record of the previous version with differences of 1.06 cm in landing and 3.7 mm in height above the net.

Table 3 compares the model with the source. The simulated rate of valid clean serves (59.3%) fell within the 95% confidence interval of the observed rate (63.9%; 55.8–71.3%). The simulated horizontal AE ( $0.28 \pm 0.21 \text{ m}$ ) matched the observed AE ( $0.26 \pm 0.21 \text{ m}$ ), independently supporting the lateral amplitude of the OU process derived from the wind tunnel. In contrast, the simulated vertical AE ( $1.49 \pm 1.30 \text{ m}$ ) was almost three times the observed AE, and when the simulated trajectories were adjusted using Eq. 1 from the source, values of 15.45 m/s and  $12.37^\circ$  were obtained instead of 17.79 m/s and  $9.87^\circ$ . This discrepancy indicates that the published parameters are parabolic fits without drag:

if interpreted as such, the mean physically equates to 19.76 m/s, 8.34°, and 2.61 m, and the contact should occur behind the baseline. Longitudinal dynamics are therefore the main structural uncertainty of the model. It was incorporated as an "observer operator" scenario (contact 1.75 m behind the baseline), instead of recalibrating the model with the same data used for comparison (Table 3).

**Table 3.** - External consistency: the model evaluated with the source measurement procedure

| Statistic (valid serves without contact) | Observed (Reiser <i>et al.</i> , 2020) | Nominal model   | Reading                    |
|------------------------------------------|----------------------------------------|-----------------|----------------------------|
| Valid serves without contact (%)         | 63.9 (55.8–71.3)                       | 59.3            | Consistent                 |
| Horizontal AE, mean $\pm$ SD (m)         | 0.26 $\pm$ 0.21                        | 0.28 $\pm$ 0.21 | Consistent                 |
| Vertical AE, mean $\pm$ SD (m)           | 0.52 $\pm$ 0.35                        | 1.49 $\pm$ 1.30 | Dissenting (overestimates) |
| Speed readjusted with Eq. 1 (m/s)        | 17.79                                  | 15.45           | Disagreeing (operator)     |
| Angle readjusted with Eq. 1 (°)          | 9.87                                   | 12.37           | Disagreeing (operator)     |
| SD speed readjusted; angle               | 0.64; 2.15                             | 0.88; 2.34      | Next                       |

**Note:** AE: anticipation error (fit to the first 7 m; extrapolation to the 0.7 m plane). For the model, 5,000 trajectories on the baseline, sampled at 100 Hz. No statistics were used to set parameters.

#### *Baseline, network, and sources of variability*

At baseline, P(valid) was 62.55% (95% CI: 62.12–62.97%): 59.04% without contact and 3.51% after touching the net. The ball touched the net in 21.04% of trajectories, and some of these contacts were valid according to Rule 10.2; therefore, P(geometric clearance without contact) (78.96%) does not equate to the probability of not missing at the net. 17.52% of balls did not clear the net, and 19.92% went out of bounds. With the serve directed to the center of the court, lateral and out-of-bounds exits were <0.01%. P(deep) was 57.56%, and P (deep | valid) was 92.03% (Table 4).

Without variability, the average serve was always valid (100.00%). Isolated aerodynamic disturbance reduced P(valid) to 85.37%, isolated technical variability to 73.39%, and their combination to 62.55%: the losses are not additive because a trajectory close to the net or baseline is displaced by moderate disturbances. Reducing technical variability by 25%

and 50% increased  $P(\text{valid})$  to 70.21% and 77.82%, respectively. These are counterfactual scenarios of the model, not the effects of an intervention. Extreme variations of net contact changed  $P(\text{valid})$  between 60.49% and 63.24%, and the lower bound with no valid contacts was 59.04%.

### *Extended response surface and search domain*

In the full net,  $P(\text{valid})$  increased monotonically towards low speeds and high angles, and its maximum (98.4%) appeared at 14.6 m/s and 20.0°, at the edge of the net and 5.10 SD from the nearest player (Figure 2a). The model, on its own, does not have an inner optimum for  $P(\text{valid})$ : a slow, lobbed serve is almost always valid, but it falls outside the observed repertoire and, according to the source, below the speeds associated with float. Therefore, the execution domain is an explicit methodological decision. The multi-objective commitment shifted with the domain: 16.6 m/s and 13.0° at [missing information]  $D_1$ , 16,2  $\frac{m}{s}$  y 14,5° en  $D_2$  y 15,8  $\frac{m}{s}$  y 16,5° en  $D_3$ . In  $D_2$ , the best performing cells were within the ellipse of player 8, the one with the lowest average speed and highest angle, so the candidate region rests mainly on the repertoire of one player.

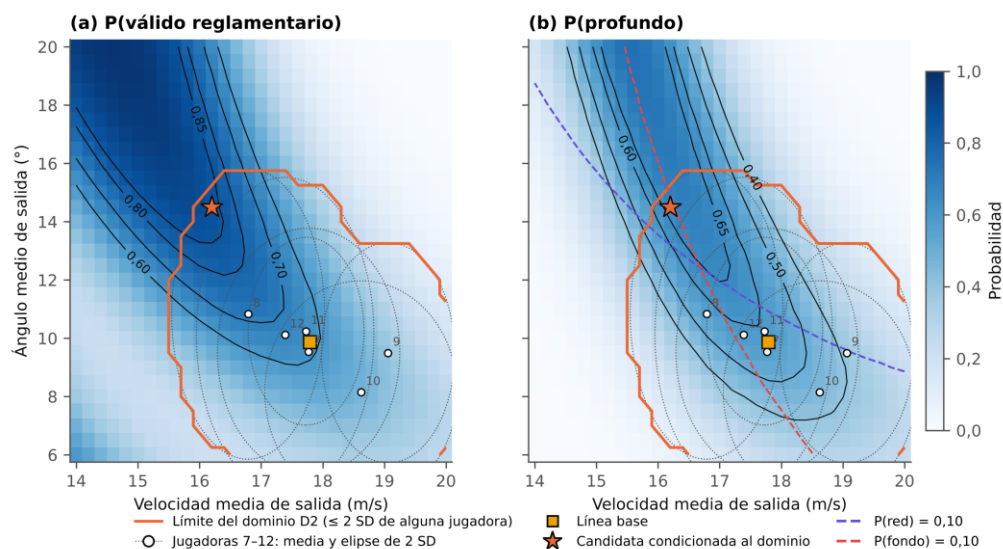


**Figure 2.** - Simulated probabilities on the enlarged grid ( $N = 4000$  per cell). (a)  $P$  (valid by regulations); (b)  $P$  (deep), with the isolines of  $P(\text{net}) = 0.10$  and  $P(\text{bottom}) = 0.10$ . The orange line delimits the empirical domain  $D_2$ . The dotted ellipses represent  $\pm 2$  SD for each player.

### *Domain-conditioned candidate configuration*

With  $N = 50,000$ , the candidate at 16.2 m/s and  $14.5^\circ$  ( $d = 1.75$  SD of player 8) obtained  $P(\text{valid}) = 87.25\%$  (95% CI: 86.95–87.54%),  $P(\text{deep}) = 67.76\%$ ,  $P(\text{does not clear the net}) = 3.98\%$ , and  $P(\text{depth}) = 8.77\%$  (Table 4). Compared to the baseline, the paired differences were +24.70 pp (+24.32 to +25.08) in  $P(\text{valid})$ , +10.20 pp in  $P(\text{deep})$ , –13.54 pp in  $P(\text{net})$ , and –11.15 pp in  $P(\text{depth})$ . The improvement came from reducing network failures without shifting them to the bottom line, which distinguishes a compromise from a single-objective solution.

The choice within the region was sensitive to preferences. The 16.0 m/s;  $14.5^\circ$  cell maximized  $P(\text{valid})$  (89.21%; +1.97 pp vs. the candidate, 95% CI: 1.79–2.15), but reduced  $P(\text{deep})$  by 3.79 pp. With random weights, 16.0 m/s;  $14.5^\circ$  (40.2%), 16.2 m/s;  $15.0^\circ$  (36.2%), 16.2 m/s;  $14.5^\circ$  (21.7%), and 16.0 m/s;  $14.0^\circ$  (1.1%) were selected. With the original thresholds, the practical window was reduced to one cell (16.0 m/s;  $14.5^\circ$ ). With alternative thresholds, it spanned 16.0–16.2 m/s and  $14.0$ – $15.0^\circ$ . Therefore, a candidate region of 16.0–16.2 m/s and  $14.0$ – $15.0^\circ$ , conditioned on  $D_2$ , is described, and not a single robust optimum. Its representative, according to the distance-to-ideal rule with equal weights, is 16.2 m/s and  $14.5^\circ$ .

**Table 4.** - Probabilities (%) of all outcomes in the baseline and in the candidate region

| Configuration                                       | d (SD)      | P(valid) (95% CI)          | Valid without contact | Valid with contact | Does not pass the network (95% CI) | Fund (95% CI)           | Side + antenna   | Deep (95% CI)              | Deep   valid |
|-----------------------------------------------------|-------------|----------------------------|-----------------------|--------------------|------------------------------------|-------------------------|------------------|----------------------------|--------------|
| Baseline: 17.79 m/s; $9.87^\circ$                   | 0.16        | 62.55 (62.12–62.97)        | 59.04                 | 3.51               | 17.52 (17.19–17.86)                | 19.92 (19.58–20.28)     | < 0.01           | 57.56 (57.13–58.00)        | 92.03        |
| <b>Candidate: 16.2 m/s; <math>14.5^\circ</math></b> | <b>1.75</b> | <b>87.25 (86.95–87.54)</b> | <b>85.91</b>          | <b>1.33</b>        | <b>3.98 (3.82–4.16)</b>            | <b>8.77 (8.53–9.02)</b> | <b>&lt; 0.01</b> | <b>67.76 (67.35–68.17)</b> | <b>77.67</b> |
| 16.0 m/s; $14.5^\circ$                              | 1.95        | 89.21 (88.94–89.48)        | 87.55                 | 1.67               | 5.20 (5.00–5.39)                   | 5.59 (5.39–5.79)        | < 0.01           | 63.97 (63.55–64.39)        | 71.70        |
| 16.0 m/s; $14.0^\circ$                              | 1.80        | 88.25 (87.96–88.53)        | 86.13                 | 2.12               | 7.27 (7.04–7.50)                   | 4.49 (4.31–4.67)        | < 0.01           | 60.91 (60.49–61.34)        | 69.03        |
| 16.2 m/s; $15.0^\circ$                              | 1.93        | 86.82 (86.52–87.12)        | 85.81                 | 1.01               | 2.67 (2.53–2.81)                   | 10.51 (10.24–10.78)     | < 0.01           | 69.38 (68.98–69.78)        | 79.91        |

*Note:  $N = 50,000$  per configuration, with common random numbers. Denominator: all trajectories; the six categories are mutually exclusive and sum to 100%. Wilson's IC (Monte Carlo error only). "Lateral + antenna": upper limit of IC  $< 0.01\%$  with central direction ( $y_0 = 3.5$  m); line - directed scenarios are described in section 3.7.  $d$ : distance to nearest player.*

#### *Uncertainty of source, individual variation, and scenarios*

The hierarchical bootstrap yielded intervals of 17.25–18.45 m/s for the mean velocity, 8.92–10.56° for the mean angle, and 1.72–2.61° for the pooled angular SD. When propagated, the baseline P(valid) was 61.9% (95% uncertainty interval: 52.6–70.1%), the candidate P(valid) was 87.1% (83.1–91.4%), and the difference was 25.2 percentage points (17.8–35.6). These intervals are more than ten times wider than the Monte Carlo IC, confirming that the simulation sampling error is irrelevant compared to the parameter uncertainty.

In the individual scenarios (Table 1), the best compromise for each player within her own 2 SD ellipse always required a lower speed and a higher angle than her mean, and raised P(valid) between 12.3 and 19.2 pp. However, the common candidate was more than 2 SD away from five of the six players: the direction of the fit is common, but its magnitude is individual.

In the 21 epistemic scenarios, the paired difference between the candidate and the baseline was positive in all cases (21/21 with 95% CI  $> 0$ ; from +17.6 to +26.8 pp), while the absolute level of the candidate ranged from 57.4 to 93.3% (Figure 3). The most unfavorable case was the observer operator (39.8% vs. 57.4%). The best D<sub>2</sub> cell was located at 16.0–16.4 m/s and 14–15° in all scenarios. The maximin rule selected 16.0 m/s; 14.0° (worst case: 62.7%), and the minimum regret rule, 16.2 m/s; 14.5° (maximum regret: 6.2 pp). The comparative conclusion is therefore stable; the absolute probabilities are not.

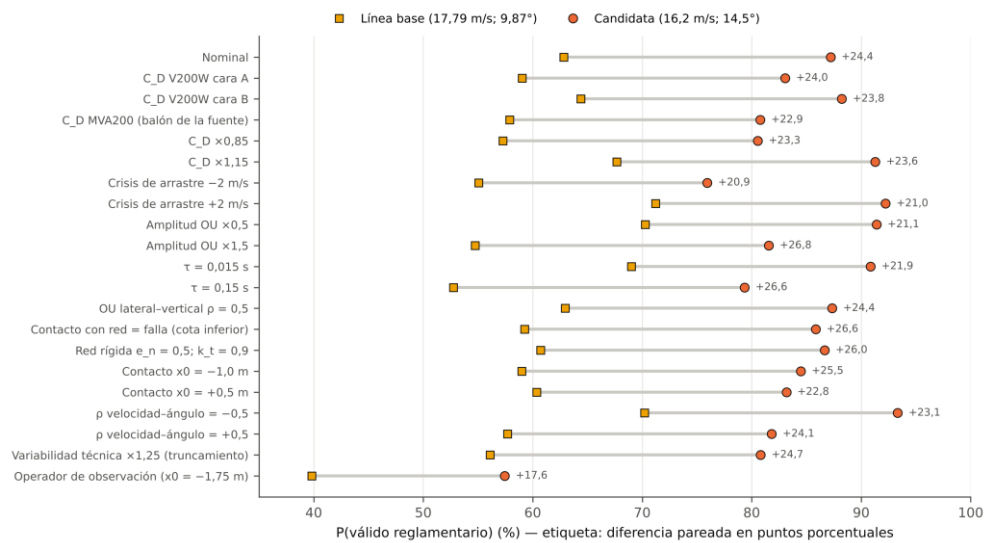


**Figure 3.** - *P (regulatory validity) of the baseline and candidate in 21 epistemic scenarios ( $N = 20,000$  with CRN). The label indicates the paired difference, with 95% CI  $> 0$  in all cases*

### Global sensitivity

In the candidate, the most influential epistemic parameters on  $P(\text{valid})$  were the displacement of the drag crisis ( $\mu^* = 0,141$ ;  $IC\ 95\ %: 0,117 - 0,167$ ), the technical variability scale (0.131), correlation time  $OU\ \tau$  (0.115), the velocity-angle correlation (0.108), and the amplitude scale;  $OU$  (0.097) the confidence intervals for the first five overlapped, so their order is not conclusive (Figure 4). The contact parameters with the net showed that  $\mu^* \leq 0,010$  the rule chosen to classify contacts had little influence on the comparison. The  $\sigma$  values, comparable to  $\mu^*$  those  $x_0$  in the drag crisis, indicate nonlinearity or interaction. In the baseline, the first position corresponded to correlation time.  $OU\ \tau$  (0.136) Consequently, the most useful measurements for reducing uncertainty would be the  $C_D$  ball-in-flight curve, the time scale of the fluctuations, the variability of attempts without truncation, the velocity-angle correlation, and the contact position.

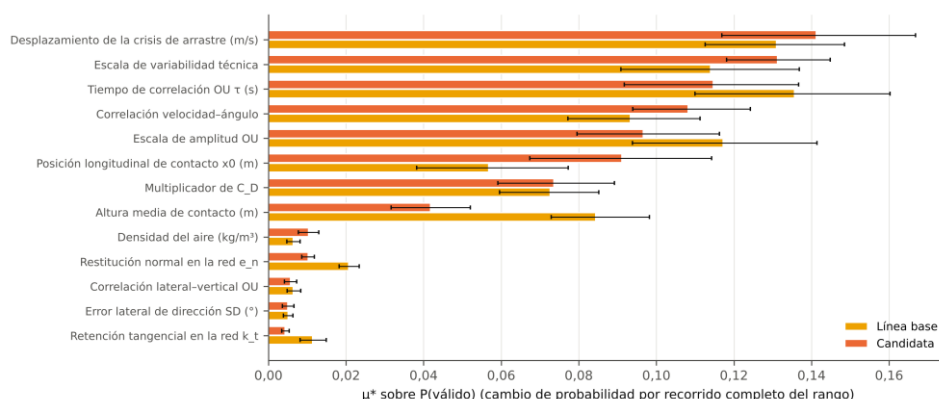


**Figure 4.** - Morris's  $\mu^*$  of 13 epistemic parameters on  $P(\text{valid})$  in the baseline and in the candidate. ( $r = 30$ ;  $p = 4$ ; IC 95 % bootstrap) The values depend on the ranges in Table 2

#### Implications for training and prospective validation

The results support a working hypothesis: slightly lowering the average speed and raising the launch angle reduces net errors without proportionally increasing baseline errors. They do not justify prescribing 16.2 m/s and 14.5° as target values. The study did not measure players or executions with this configuration, did not evaluate the induced reception quality, and did not verify whether a slower serve retains the float effect, which Reiser *et al.* (2020) associated with sufficient speed. Depth also does not equate to effectiveness: this depends on the receivers, the rotation, and the score (Fatahi *et al.*, 2022; Wang and Wang, 2025). Lateral direction matters when the serve aims for the lines: directed 1.0 m from the sideline with a 2° error, the percentage of valid serves dropped to 77.8% in the candidate (54.7% on the baseline), with 8.2% of serves going wide. Table 5 proposes a validation protocol with success criteria defined before data collection. A practice that first stabilizes performance and then introduces zone variation would be consistent with evidence on contextual interference (Qu *et al.*, 2025), although this relationship was not evaluated here.

**Table 5. - Proposed protocol for prospective validation**

| Element          | Proposed specification                                                                                                                                                 |
|------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Design           | Crossed within player: usual condition in front of the individual target band; counterbalanced order; three acquisition sessions and one retention session for 7 days. |
| Participants     | ≥ 8 competitive-level indoor players ; inclusion criteria registered prior to the study.                                                                               |
| Volume           | ≥ 45 serves per condition and player (≥ 360 per condition); power ≈ 0.80 to detect +10 pp (0.64 → 0.74; $\alpha = 0.05$ ) before the design effect.                    |
| Instrumentation  | Radar or 3D vision ≥ 100 Hz (speed, angle and contact height); landing and net contact record; V200W balloon with controlled pressure; temperature and humidity.       |
| Outcomes         | Primary: P(valid) according to Rule 10.2. Secondary: P(deep), dispersion of $\nu\theta$ , floating effect (AE) and reception quality (6-level scale).                  |
| Analysis         | Generalized linear mixed binomial model with random player effect; contrast with the probabilities predicted by the model for the actually measured performance.       |
| Success criteria | Improvement ≥ 5 pp in P(valid) without worsening the quality of induced reception (95% CI) and consistency between predicted and observed probabilities.               |

**Note:** The model configuration is used as a starting hypothesis and is individualized with the measured variability.

### Limitations

First, the empirical basis is from six players in a single study, with missed serves excluded and no published correlations. Second, the longitudinal dynamics do not reproduce the vertical statistics from the source (section 3.1); the observation operator scenario limits this problem, but does not solve it. Third, the OU process, the  $C_D$  tunnel curve with a stationary ball, and the contact model with the sideline are uncalibrated surrogate models with their own trajectories. Fourth, ball attitude, residual rotation, and deformation were not modeled. Fifth, the initial conditions are derived from the MVA200 and the nominal aerodynamics from the V200W; the MVA200 scenario reduced the absolute levels, but not the direction of the effect. Sixth, the study estimated validity and depth, not competitive effectiveness, and should not be extrapolated to men, formative categories, sitting volleyball, or beach volleyball (Drikos). *et al.*, 2025; Giatsis *et al.*, 2023; Li *et al.*, 2026).

## **CONCLUSIONS**

In a numerically verified model, whose validity rate and lateral deviation are consistent with the source, combinations with slightly lower speed and a higher angle than the observed average increased the simulated probability of a valid serve according to FIVB Rule 10.2. This comparative conclusion held true across all 21 epistemic scenarios and the six players analyzed individually. The exact location of the recommended configuration, however, depends on the admitted domain: without empirical restriction, it shifts to the explored edge and, within the  $\pm 2$  SD domain, is situated in a region of 16.0–16.2 m/s and 14.0–15.0° (representative: 16.2 m/s and 14.5°;  $P(\text{valid}) = 87.25\%$ , with a parametric uncertainty interval of 83.1–91.4%). This region is primarily derived from one player's repertoire; the 14.5° angle is demanding, and none of it has been validated on the court. The probabilities should be understood as model estimates, not as expected performance, and the proposed configuration as a hypothesis for an individualized prospective protocol, which should also measure the quality of reception.

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*Conflict of interest:*

The author declares that there is no conflict of interest related to the content of the manuscript.

*Statements*

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the simulation engine, input data, digitized curves, seeds, scripts that regenerate each table and figure, intermediate results and traceability table are attached in full to this submission as a reproducible package and have reserved in Zenodo the DOI <https://doi.org/10.5281/zenodo.23676005>, which will be activated upon publication of the article (code: MIT; data: CC BY 4.0).

*Authorship contribution:*

Alberto David Quesada Paz: conceptualization, methodology, software, formal analysis, research, visualization, drafting, review and editing.

*Use of artificial intelligence:*

Artificial intelligence tools were used to support programming, linguistic review, and consistency verification. Methodological decisions, interpretation, and approval of the text are the responsibility of the author. All figures are taken from the deposited code.