How to achieve the most effective serve in women's volleyball.

Daniela Monterosso

At all levels of volleyball, a key defining factor of the competency of a team is their ability to serve effectively and efficiently[1]. Each of our volleyball trainings are therefore comprised of hours of repetitive serving to improve this "most important skill". In this essay I will aim to discuss what the ideal serve would look like at various levels of volleyball, with the goal of maximising the number of aces. To do so, I will use a computational model to explore the ideal ball trajectory and the optimal initial angle from the horizontal axis.

! ***Ace*** *– When a serve is not returned by the opposing team. Can be* ***shanked*** *by the opponent (ball hits the receiver's arms and goes flying off in the complete wrong direction before landing on the floor) or can be a* ***no-touch ace*** *(ball lands directly on the floor in the court and - pretty intuitively - without being touched by anyone)*

Firstly, it is important to ask what constitutes an effective serve? The best people that can inform us on serve receive are the Liberos.

! ***Libero*** *– a position which only receives serves and hits and therefore normally the best passer in a team, typically the shortest or fastest person on the team that wears a different coloured jersey.*

Having asked my libero friends as well as through observation of other liberos during our matches, I have concluded that the most difficult serves to receive are ones which travel very close to the net tape, land far in the court, close to the edges of the court, and as fast as possible.

In volleyball, there are 2 main serves that can be performed which are:

! ***Float or jump float serve*** *– a serve in which the ball travels without spin, usually drops fairly fast due to air resistance, and sways slightly side to side also due to the lack of spin. A jump float is the same thing but with a slight hop to hit the ball with a higher contact point and therefore bringing it closer to the tape at a faster speed.*

! ***Top spin serve*** *– The ball is served very fast with lots of topspin which in turn causes the Magnus[2] force to be produced. It is very speedy but it is easier to predict its flight path as the fast spinning allows no side to side motion like in the float serve.*

---

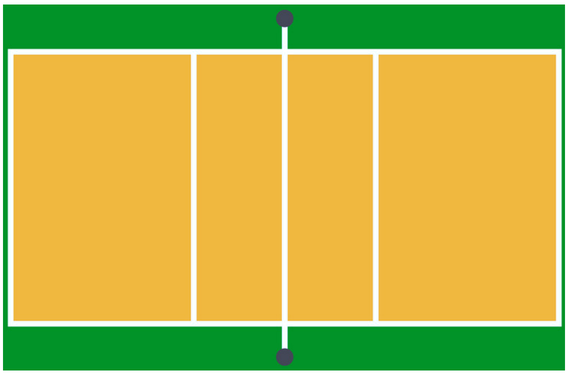
1 Coach Carlos Johnson [my coach], "The most important skills in volleyball are serve, serve receive and outside hitting, with the most important being serving".

2 The name given to the force produced due to the pressure gradient caused by the ball spinning; it is what causes a ball hit with top spin to come down very quickly. Eiley S. Physics of Free Kicks - Stem Fellowship [Internet]. STEM Fellowship. 2022. Available from: https://live.stemfellowship.org/physics-of-free-kicks/

It is widely recognised by players and coaches, that the most effective serve in women's volleyball at all levels, from U14 to International competitions, is the jump float serve[3]. Unless you are Melissa Vargas and capable of producing inhumane speeds[4], a jump float is usually a better choice. Whereas, in the men's game especially at a higher level you would see most men topspin serving. This is because on average they can hit the ball with such speed to produce such a significant Magnus force that even if the receivers know the direction, they do not have enough time to place themselves in a good receiving position. In this essay, however, I will be referencing women's volleyball and the jump float serve. While the side-to-side motion of the ball is rather unpredictable, as it is due to air turbulence, this doesn't significantly affect the distance the ball will travel. The dropping of the ball is more significant and is therefore the main focus of the essay. The effect of the drag force is what most impacts the distance the ball travels.

The final thing that needs to be specified before diving into the maths and physics of a serve is the court constraints which are:

1. The official size of an indoor volleyball court is 9m by 18m.
2. The net is in the middle of the court at the 9m mark and for women at a height of 2.24m (men's 2.43m)
3. The server cannot cross the service line (the back line) with their feet on a serve, even though the ball is normally tossed into the court and the server jumps over the line when serving, for the purposes of this essay I will picture the ball being contacted directly above the service line, at an average height of 2.50m (from observation).



(Image from google)

Having discussed all important aspects of the volleyball serve, it is safe to start implementing some equations to help us understand the maths and physics of what is going on.

---

[3] Coach Carlos Johnson.

[4] She holds the world record for the fastest serve in women's volleyball at 112km/h.

[1] Basic motion of a ball in a vacuum

With negligible air resistance the trajectory of a ball can be described very simply with a small set of equations that any A Level maths and physics student would know like the back of their hand, the SUVAT equations (using vectors)[5].

Firstly, we can describe the acceleration of an object under only the force of gravity (as we are imagining we are in a vacuum) as:

$$\vec{a} = \begin{pmatrix} 0 \\ -g \end{pmatrix}$$

Next, we can describe our initial velocity, u of a projectile (in our case a volleyball) fired at angle θ as:

$$\vec{u} = \begin{pmatrix} ucos\theta \\ usin\theta \end{pmatrix}$$

We can then use these vectors to derive our equation of motion of a projectile:

$$\vec{r} = \vec{u}t + \frac{1}{2}\vec{a}t^2$$

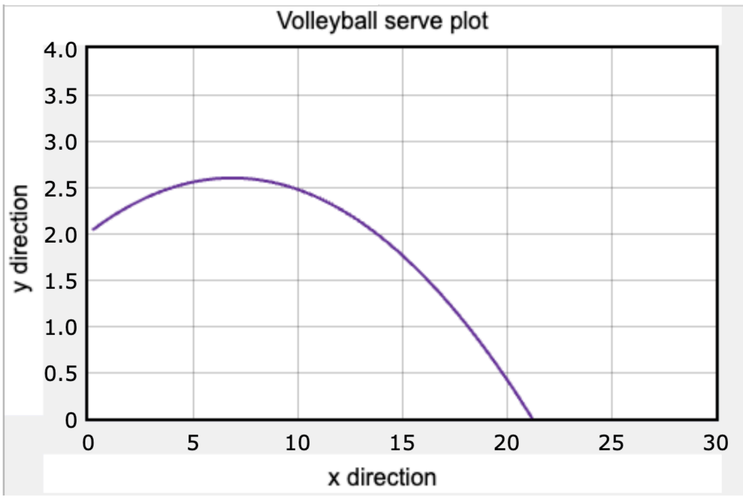
$$\begin{pmatrix} x \\ y \end{pmatrix} = t\begin{pmatrix} ucos\theta \\ usin\theta \end{pmatrix} + \frac{t^2}{2}\begin{pmatrix} 0 \\ -g \end{pmatrix}$$

Another quick equation that is not a SUVAT equation but would still be useful to define, before making things more complicated, is the equation for Newton's 2nd law of motion:

$$F = ma$$

Before I start plotting more complicated trajectories, we should also explore the normal trajectory of a projectile with no external forces, aside from gravity:

[5] Attwood G, Bettison I, Clegg A, Dyer G, Dyer J, Gallick K. Edexcel A Level Mathematics Statistics & Mechanics Year 2 Textbook + e-book. Harlow, United Kingdom: Pearson Education Limited; 2017.



(Made by me on trinket.io, based off of a dot physics video https://www.youtube.com/watch?v=zaIoxnKVY1w)

A typical projectile without any external forces, follows the shape of a neat parabola, with our x and y coordinates being easily plotted using the SUVAT equations.

[1.1] What if air resistance is not negligible?

As most of you will have observed, a key point in this explanation is the implication that the ball has negligible air resistance. If a ball, in our case a volleyball, moves through the air it exerts a force on the air particles. According to Newton's 3rd law, the air particles exert an equal and opposite force on the ball. This force is more commonly known as air resistance or drag. This drag can be either linear or quadratic drag. With linear drag, the force of drag is proportional to the velocity, whereas with quadratic drag the force of drag is proportional to the square of the velocity. Whether linear or quadratic drag is used depends on a number called Reynold's number. This is defined as:

$$Re = \rho d v / \eta$$

Where d is the diameter of the volleyball, ρ is the density of the fluid, v is the velocity of the fluid and η is the kinematic viscosity. For very low Reynold's number, formulas for linear drag can be used, whereas for high Reynold's number quadratic drag can be used. A low Reynold's number would apply to microorganisms moving through a more viscous fluid than air such as water. A high Reynold's number however, could be that of a skydiver. For a volleyball, the Reynold's number would be[6]:

$$Re \approx 2.8 \times 10^5$$

[6] Hong S, Weon B, Nakanishi Y, Kimachi K, Seo K, Asai T. AERODYNAMIC EFFECTS OF A PANEL ORIENTATION IN VOLLEYBALL FLOAT SERVE [Internet]. p. 1. Available from: https://sprinz.aut.ac.nz/__data/assets/pdf_file/0008/203021/143_1378_Hong.pdf

Since Reynolds number is $10^3<Re$ and not $Re<1$, We use quadratic drag to predict the motion of our volleyball. Therefore, the formula for drag force that we need is defined as[7]:

$$Fd = \frac{1}{2}CdA\rho v^2$$

Where Fd is the drag force, Cd is the drag coefficient, A is the cross-sectional area, v is the velocity of the ball, and ρ is the density of the fluid. This formula can be edited to be in vector format[8]:

$$Fd = \frac{1}{2}CdA\rho|v|\vec{v}$$

This formula can then be used to give the acceleration due to the drag force[8]:

$$|V^2| = Vx^2 + Vy^2$$
$$|V| = \sqrt{Vx^2 + Vy^2}$$
$$|V|\vec{V} = \sqrt{Vx^2 + Vy^2} \times \begin{pmatrix} Vx \\ Vy \end{pmatrix}$$
$$\overrightarrow{Fd} = \frac{1}{2}CdA\rho \times \sqrt{Vx^2 + Vy^2} \times \begin{pmatrix} Vx \\ Vy \end{pmatrix}$$

$$\overrightarrow{Fd} = m\vec{a}$$
$$ay = \frac{1}{2m}CdA\rho \times \sqrt{Vx^2 + Vy^2} \times Vy$$
$$ax = -\frac{1}{2m}CdA\rho \times \sqrt{Vx^2 + Vy^2} \times Vx$$

The drag force acts in the vertical and horizontal directions. It opposes the motion of the ball so in calculation it is negative in the x direction and positive in the y direction.

[2] Plotting motion

I will use various values to test the trajectory and find out ultimately what the ideal serve would be:

1. 33mph = a typical junior serving speed, (14.75 ms^{-1})[9]

---

[7] Timmerman P, van der Weele JP. On the rise and fall of a ball with linear or quadratic drag. American Journal of Physics [Internet]. 1999 Jun;67(6):538. Available from: https://ris.utwente.nl/ws/portalfiles/portal/6689298/Timmerman99on.pdf

[8] Dr Bell. King's College School [My maths teacher].

2. 39mph = weak NCAA women's serving speed, (17.43 ms^{-1})[10]
3. 42mph = strong NCAA women's serving speed, (18.78 ms^{-1}) [10]

! ***NCAA*** *– National Collegiate Athletic Association (Includes University level volleyball in America)*

For each serve I will use the computer program to estimate, through testing, what the initial angle is that is needed for the ball to land deep in the court, at 17m from the service line (1m from the base line as "seam allowance", a typical strong serve). I will also consider a ball that lands at the base line at 18m from the service line (the most extreme angle the ball can be contacted before hitting the ball out). I am assuming the server's hand contacts the ball at 2.50m, as this is more or less the average contact point of a float serve.

[2.1] Values needed for drag force calculations

Before I plot, we must first establish our values for the drag force. We can take: Cd = 0.16[11], ρ = 1.293kgm^{-3} [12], A = $(0.1^2 \times \pi)m^2$ [13], m = 0.270kg [13].

[2.2] Code for these graphs

Web VPython 3.2

```
#creates graphs to plot
g1 = graph(title = "Volleyball serve plot", xmin = 0,
xmax = 20, ymin = 0, ymax = 20, xtitle = "x direction",
ytitle = "y direction")

f1 = gcurve(color = color.orange)
f2 = gcurve(color = color.purple)

#Motion vectors, g, r, and v
g = vector(0, -9.8, 0)
r = vector(0, 2.5, 0)
u = 14.75
```

---

[11] Hong S, Weon B, Nakanishi Y, Kimachi K, Seo K, Asai T. AERODYNAMIC EFFECTS OF A PANEL ORIENTATION IN VOLLEYBALL FLOAT SERVE [Internet]. p. 1. Available from: https://sprinz.aut.ac.nz/__data/assets/pdf_file/0008/203021/143_1378_Hong.pdf

[12] Baynes K. Air Mass/Density | NASA Earthdata [Internet]. NASA Earthdata. 2024. Available from: https://www.earthdata.nasa.gov/topics/atmosphere/air-mass-density

[13] Dimensions.com. Volleyball Dimensions & Drawings | Dimensions.com [Internet]. www.dimensions.com. 2020. Available from: https://www.dimensions.com/element/volleyball

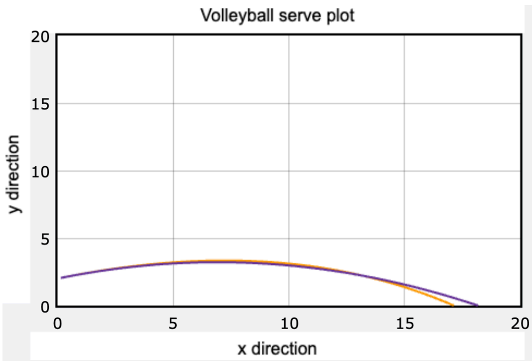
```
theta = 18.5*pi/180
ux = u*cos(theta)
uy = u*sin(theta)

v = vector(ux, uy, 0)

#Calculating CdAp/2m
m = 0.27
d = 0.16
A = 0.1**2*pi
rho = 1.293
mass = (1/(2*m))
totDrag = d*A*rho*mass

#Vector for drag force
drag = vector(-totDrag*sqrt(ux**2 + uy**2)*ux, totDrag*sqrt(ux**2 + uy**2)*uy, 0)

#time increments
t = 0
dt = 0.01

while t<2.65:
  #motion of the ball with drag
  v = v + g*dt + drag*dt
  r = r + v*dt
  t = t +dt
  f1.plot(r.x, r.y)

r2 = vector(0, 2.5, 0)
u2 = 14.75
theta2 = 18.5*pi/180
ux2 = u*cos(theta2)
uy2 = u*sin(theta2)
v2 = vector(ux2, uy2, 0)

t = 0
dt = 0.01

while t<2.65:
  #motion of the ball without drag
  v2 = v2 + g*dt
  r2 = r2 + v2*dt
  t = t +dt
  f2.plot(r2.x, r2.y)
```

The code was made by me with some external internet help[14]. Overall, the code uses a few simple variables and functions to calculate the trajectory fairly accurately. I edited the initial velocity (u = 14.75) and the angle (theta = 22*pi/180) at which the ball is hit to find the fairly exact angle at which the ball needs to be hit to land in specific areas of the court. The program then uses vectors for velocity (v = vector(ux, uy, 0)), gravity (g = vector(0, -9.8, 0)), position (r = vector(0, 2.5, 0)) and deceleration due to drag (drag = vector(-totDrag*sqrt(ux**2 + uy**2)*ux, totDrag*sqrt(ux**2 + uy**2)*uy, 0)) to calculate the trajectory which is then plotted on a graph.

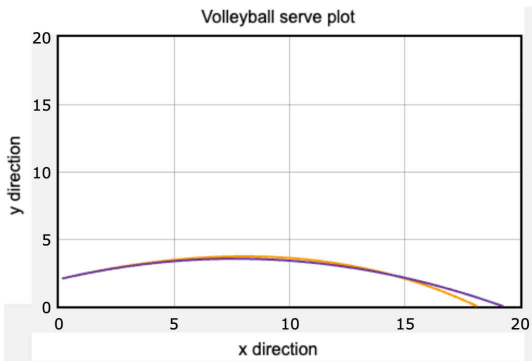
[2.3] Graphs and data

The data can now be collected and inserted in a table. For reference, orange is the ball with drag and purple would be the ball without drag, to show the impact drag has on the trajectory of the ball, all images are from the same computer program:

33mph 17m = 18.5° :

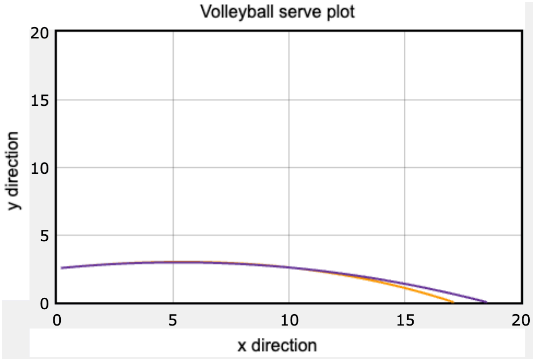


33mph 18m = 21° :

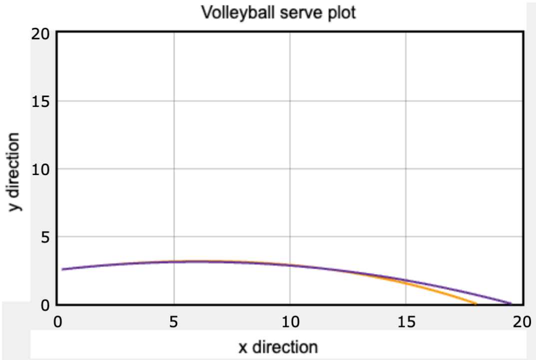


[14] Dot Physics. Projectile Motion with Vectors and Python [Internet]. YouTube. 2023. Available from: https://www.youtube.com/watch?v=zaIoxnKVY1w

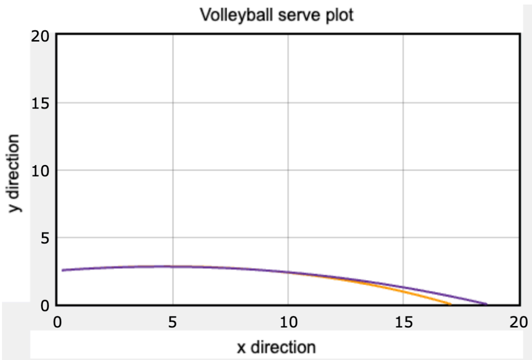
39mph 17m = 10° :



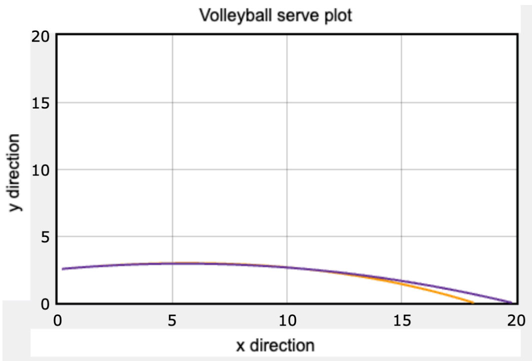
39mph 18m = 11.5° :



42mph 17m = 7.5° :



42mph 18m = 9° :



		Distance from serving base line/m	
		17	18
Serve speed/mph	33	18.5°	21°
	39	10°	11.5°
	42	7.5°	9°

(Data from me in excel)

[3] Conclusion

As I mentioned at the beginning, both passers and coaches agree that the most effective serve is one that is fast, that lands deep in the court, and comes close to the side line. By this standard, the most effective serve at a junior level is a 33mph serve that is hit at an initial angle between 18.5° and 21°. Similarly, the most effective serve at the NCAA level is at 42mph serve that is hit between 7.5° and 9°.

This method can be applied to higher or lower levels of volleyball for a wider spread of data. It would be interesting to see a similar method applied to the topspin serve by adding a vector for the Magnus force and calculating the force due to the spinning ball. Maybe this will be my next endeavour!