

The Physics of Racket–Shuttle Energy Transfer in Badminton

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Abstract

Shuttle exit speed in a badminton smash is set almost entirely by racket-head speed at the impact point; equipment changes only the multiplier between the two, which lies between about 1.3 and 1.8. We model the 1–1.4 ms contact as a one-dimensional collision between the shuttle (mass $m \approx 5.1$ g) and the racket’s effective mass at the impact point ($M_e \approx 42$ g), characterised by a coefficient of restitution e . Published smash data (racket head 52 m/s, shuttle 80.5 m/s) imply $e \approx 0.7$. A mass–spring treatment of the contact gives a combined stiffness of about 3×10^4 N/m, peak forces near 600 N and about 2 cm of combined deformation. Because the shuttle is far lossier than the strings, a softer string bed (lower tension) stores more of the collision energy in the efficient element and raises e ; experiments find shuttle speed falls by up to about 10% as tension rises from 20 to 34 lbf. Thinner strings help slightly, by an estimated 1% across the commercial range of gauges, mainly because they are lighter rather than softer. Heavier swingweight lowers head speed but raises effective mass, and the two effects roughly cancel. We argue that the manufacturers’ term “repulsion” corresponds most closely to the coefficient of restitution (Japanese 反発係数, literally “repulsion coefficient”) of the strung racket, together with string-bed stiffness and energy return.

1. Introduction and notation

Racket and string makers describe performance in terms of “repulsion”, “power”, “control”, “durability” and “hitting sound”. This note sets out the mechanics behind the first two: how momentum and energy pass from racket to shuttle, and which racket and string properties change the result. Every symbol and abbreviation used below is defined here; typical values are those used in the worked examples.

1.1 Abbreviations

Abbrev.	Meaning
COR	Coefficient of restitution: the ratio of the speed at which two colliding bodies separate to the speed at which they approached, measured at the contact point (symbol e)
ACOR	Apparent coefficient of restitution: shuttle rebound speed divided by incident speed when the shuttle is fired at a stationary, freely held racket (symbol e_A)
CM	Centre of mass
MoI	Moment of inertia (rotational inertia about a stated axis)
KE	Kinetic energy
FE	Finite element (computer simulation method)
SD	Standard deviation
lbf	Pound-force, the unit of string tension on stringing machines; 1 lbf = 4.448 N, so 24 lbf ≈ 107 N
fps	Frames per second (camera)

1.2 Symbols

Symbol	Meaning	Typical value
m	Mass of the shuttle	4.74–5.50 g; 5.1 g used
M	Total mass of the strung racket	85–95 g; 90 g used
M_e	Effective mass of the racket at the impact point: the mass of a free particle that would respond to the impulse exactly as the racket's impact point does	≈ 42 g at head centre
r	Mass ratio m/M_e	≈ 0.12
μ	Reduced mass $mM_e/(m + M_e)$	≈ 4.6 g
V	Speed of the racket at the impact point, normal to the string bed, just before impact (V' just after)	≈ 52 m/s in a good smash
u	Speed of the incoming shuttle towards the racket	0 for a hanging shuttle
v	Speed of the shuttle just after impact (exit speed)	≈ 80 m/s
e	COR of the racket–shuttle collision	≈ 0.5 – 0.7
e_A	ACOR, defined in Eq. (6)	≈ 0.5
d	Distance from the butt of the handle to the racket CM	≈ 30 cm
b	Distance along the racket's long axis from the CM to the impact point	≈ 25 cm at head centre
c	Sideways distance of the impact point from the long axis	0 for an on-axis hit
I_{cm}	MoI about an axis through the CM, parallel to the string bed and perpendicular to the shaft	≈ 52 kg cm ²
I_s	Swingweight: MoI about a parallel axis 9 cm from the butt	90–97 kg cm ²
I_P	Polar MoI about the racket's long axis (resistance to twisting)	≈ 1.8 kg cm ²
ω	Angular velocity of the racket during the swing	≈ 110 rad/s
J	Impulse: the integral of contact force over time, equal to the shuttle's change in momentum	≈ 0.41 N s
F	Contact force between strings and shuttle	peak ≈ 500 – 650 N
τ	Contact (dwell) time	1.0–1.4 ms
k	Spring constant (stiffness) of the whole contact, string bed and shuttle in series: force per unit compression	$\approx 3 \times 10^4$ N/m
k_s	Spring constant (stiffness) of the string bed alone	of order 10^4 N/m
k_b	Spring constant (stiffness) of the shuttle alone (cork plus feather skirt)	not measured
e_s, e_b	COR of the string bed alone and of the shuttle alone; e^2 is the fraction of stored elastic energy returned	e_s high (≈ 0.9), e_b low
f_s, f_b	Fractions of the collision energy stored in the string bed and in the shuttle	$f_s + f_b = 1$
x	Transverse deflection of a string at the contact point	≈ 1 cm
T	Tension in a string (in newtons; machine settings quoted in lbf)	20–30 lbf = 89–133 N
L	Free length of a string between frame holes	≈ 0.2 m
E	Young's modulus of the string material	≈ 4 GPa (assumed)
A	Cross-sectional area of a string, $\pi d_s^2/4$	0.29–0.39 mm ²
EA	Axial stiffness of a string: force per unit fractional stretch	≈ 1.2 – 1.5 kN (estimate)
f_n	Fundamental bending frequency of the freely held racket	50–55 Hz
d_s	String diameter (gauge)	0.61–0.70 mm
ρ	Density of the string material (nylon)	≈ 1140 kg/m ³
λ	Linear density (mass per unit length) of a string, ρA	0.33–0.44 g/m

continued overleaf

Symbol	Meaning	Typical value
σ	Tensile stress in a string, T/A	$\approx 280\text{--}370$ MPa at 24 lbf
c_w	Speed of transverse waves along a string, $\sqrt{T/\lambda}$	$\approx 500\text{--}570$ m/s
f_1	Fundamental vibration frequency of a single string, $c_w/2L$	$\approx 1.1\text{--}1.3$ kHz
m_{str}	Moving mass of the strings engaged by the shuttle	$\approx 0.3\text{--}0.4$ g

2. Typical parameters

The shuttle is roughly one-eighteenth of the racket’s mass and is in contact with it for about a millisecond (Table 1).

Table 1: Typical parameters used in the worked examples.

Quantity	Value	Source
Shuttle mass m	4.74–5.50 g (Laws of Badminton)	[21]
Racket mass M	0.085–0.095 kg	[7]
Swingweight I_s (axis 9 cm from butt)	90–97 kg cm ²	[7]
Polar MoI I_P	≈ 1.8 kg cm ²	[7]
Racket fundamental frequency f_n (free)	$\approx 51\text{--}54$ Hz	[7]
Contact time τ	≈ 1 ms (high-speed video); 1.4 ms assumed at 15,000 fps	[10, 7]
Racket-head speed V , smash	52.0 ± 5.3 m/s (20 regional to international players)	[7]
Shuttle exit speed v , smash	80.5 ± 8.2 m/s (same players)	[7]
Ratio v/V , smash	≈ 1.55	derived
Ratio v/V , slow linear “drop shot”	≈ 1.35	[19]

The effective-mass calculations below assume $M = 90$ g, $d = 30$ cm and $I_s = 92$ kg cm². The parallel-axis theorem then gives $I_{cm} = I_s - M(d - 0.09 \text{ m})^2 \approx 52$ kg cm². The head centre is taken as 55.5 cm from the butt, so $b \approx 25.5$ cm. These are representative, not measured, values for a specific racket.

3. Rigid-body impact model

Treating the racket as a free rigid body and the contact as a one-dimensional collision gives a closed-form exit speed, Eq. (5), with only three equipment parameters: e , m and M_e .

3.1 Why the hand can be ignored

During contact a transverse bending wave runs from the impact point to the handle and back. If the shuttle has left before the reflected wave returns, the hand cannot influence the exit speed. In tennis, with a dwell time near 8 ms, this already holds closely, and the handheld racket vibrates at frequencies much nearer the free racket than the clamped one [1, 2, 4]. Badminton contact is about eight times shorter, so the free-body model is even better here. Grip firmness therefore does not change exit speed; it matters only for racket speed before impact.

3.2 Effective mass at the impact point

Let an impulse J act on the racket, opposing its motion, at distance b along the long axis from the CM and distance c to one side. The CM velocity changes by $-J/M$, the rotation about the transverse axis by $-Jb/I_{cm}$, and the twist about the long axis by $-Jc/I_P$. The velocity of the impact point therefore changes by $-J/M_e$, where

$$\frac{1}{M_e} = \frac{1}{M} + \frac{b^2}{I_{cm}} + \frac{c^2}{I_P}. \quad (1)$$

Table 2 evaluates Eq. (1) with the values of Section 2.

Table 2: Effective mass at different impact points.

Impact point	b (cm)	c (cm)	M_e (g)	$r = m/M_e$
5 cm below head centre	20	0	53	0.10
Head centre	25.5	0	42	0.12
5 cm above head centre	30	0	35	0.14
Head centre, 2 cm to one side	25.5	2	39	0.13
Head centre, 4 cm to one side	25.5	4	31	0.16

The small polar MoI I_P makes off-axis hits costly: 4 cm sideways removes a quarter of the effective mass.

3.3 Exit speed

Take the racket’s direction of travel as positive. Before impact the impact point moves at V and the shuttle at $-u$; afterwards they move at V' and v . The COR is defined [4] as

$$e = \frac{v - V'}{V + u}, \quad (2)$$

and momentum conservation during the brief contact gives

$$M_e V - mu = M_e V' + mv. \quad (3)$$

Solving (2) and (3) for v :

$$v = \frac{(1 + e) M_e V + (e M_e - m) u}{M_e + m}, \quad (4)$$

or, dividing through by M_e ,

$$v = \frac{1 + e}{1 + r} V + e_A u, \quad (5)$$

$$e_A = \frac{e - r}{1 + r}. \quad (6)$$

The factor e_A is the ACOR: the fraction of an incoming shuttle’s speed returned by a stationary racket [1, 2]. Eq. (5) shows that exit speed is linear in racket speed, and that equipment acts only through e and r .

3.4 What the data imply

For a smash at a near-stationary shuttle ($u \approx 0$), Eq. (5) gives $v/V = (1 + e)/(1 + r)$. Even a perfectly elastic collision ($e = 1$) at head centre caps this ratio at $2/1.12 \approx 1.79$.

- **Smash.** The measured ratio of $80.5/52.0 \approx 1.55$ [7] implies $e \approx 0.74$. This is an upper estimate: players strike slightly beyond head centre, where the racket moves faster than the head-centre speed that was measured.
- **Slow push.** A linear “drop shot” collision gave $v/V \approx 1.35$ [19], implying $e \approx 0.51$.
- **Rebound tests.** Raising string tension from 22 to 27 lbf lowered the shuttle’s measured COR from 0.541 to 0.374 [12]. Those tests used a different set-up (a dropped shuttle), so the numbers indicate the range rather than match Eq. (2) exactly.

A working value of $e \approx 0.5$ – 0.7 is therefore consistent with all three sources.

3.5 The racket slows down

From Eq. (3) with $u = 0$, the impact point loses a fraction $r(1 + e)/(1 + r)$ of its speed: about 19%, or roughly 10 m/s in a 52 m/s smash. The shuttle is light, but not negligible.

4. Impulse, force and energy budget

The shuttle receives an impulse of about 0.41 N s, peak forces of roughly 500–650 N, and about 30% of the racket’s kinetic energy.

4.1 Impulse and force

The impulse equals the shuttle’s change of momentum:

$$J = \int_0^\tau F dt = m(v + u). \quad (7)$$

For $m = 5.1$ g, $v = 80.5$ m/s and $u \approx 0$, $J \approx 0.41$ N s. The mean force over the contact is J/τ ; for a half-sine force pulse the peak is $\pi/2$ times the mean (Table 3).

Table 3: Contact forces for the measured impulse.

Contact time τ	Mean force	Peak force (half-sine)	Shuttle acceleration
1.0 ms	≈ 410 N	≈ 650 N	≈ 8000 g
1.4 ms	≈ 290 N	≈ 460 N	≈ 5800 g

Eq. (7) makes a point that is often confused in equipment marketing. The impulse is fixed by the momentum the shuttle ends up with; a longer contact time does not add impulse, it only spreads the same impulse over longer at lower force. *Dwell time is a symptom of string-bed stiffness, not a source of power.*

4.2 Energy budget

The kinetic energy lost in the collision, in the centre-of-mass frame of the two bodies, is

$$\Delta KE = \frac{1}{2} \mu (1 - e^2) (V + u)^2, \quad (8)$$

where $\mu = mM_e/(m + M_e)$ is the reduced mass. Table 4 gives the budget for the smash of Section 2 ($e \approx 0.74$, $\mu \approx 4.6$ g).

Table 4: Energy budget for a 52 m/s smash at head centre.

Energy	Value
Effective racket KE before impact, $\frac{1}{2}M_e V^2$	≈ 57 J
Shuttle KE after impact, $\frac{1}{2}mv^2$	≈ 16.5 J
Effective racket KE after impact, $\frac{1}{2}M_e V'^2$	≈ 38 J
Lost to deformation, heat and vibration, Eq. (8)	≈ 3 J

About 29% of the racket’s effective kinetic energy reaches the shuttle; the rest stays with the racket and is absorbed in the follow-through. The ceiling on that fraction is set by the mass ratio as well as by e : even with $e = 1$, the fraction transferred is $4r/(1+r)^2$, or about 38% at $r = 0.12$.

5. The string bed as a spring

Increasing string tension makes the string bed stiffer, which pushes more of the collision energy into the lossy shuttle and so lowers e and the exit speed; experiments find up to about 10% lower shuttle speed between 20 and 34 lbf.

5.1 Contact time, stiffness and deformation

Model the contact as a linear spring of constant k compressed between the two bodies. The relative motion is then a half-cycle of simple harmonic motion at angular frequency $\sqrt{k/\mu}$, so

$$\tau = \pi \sqrt{\frac{\mu}{k}}, \quad x_{max} = \frac{(V + u) \tau}{\pi}, \quad F_{max} = k x_{max}. \quad (9)$$

With $\tau = 1.2$ ms, $\mu = 4.6$ g and $V = 52$ m/s: $k \approx 3 \times 10^4$ N/m, $x_{max} \approx 2$ cm and $F_{max} \approx 620$ N. The peak force agrees with the impulse estimate of Section 4.1, which is a useful consistency check. Here k and x_{max} describe the string bed and shuttle together; the 2 cm is shared between strings deflecting and cork and skirt compressing.

5.2 Stiffness of a tensioned string

A string of free length L and tension T , pushed sideways by x at its midpoint, resists with

$$F(x) \approx \frac{4T}{L} x + \frac{8EA}{L^3} x^3. \quad (10)$$

The first term is geometric stiffness: the tension pulling back along the slightly angled string. It is proportional to tension. The second term comes from the string stretching, which raises its tension by

$$\Delta T = \frac{2EA x^2}{L^2}. \quad (11)$$

For $T = 107$ N (24 lbf) and $L = 0.22$ m, the geometric term gives about 2000 N/m per string. A cork about 25 mm across loads several mains and crosses, and the woven bed spreads the load further, so k_s of order 10^4 N/m is plausible. Taking $EA \approx 1.2$ – 1.5 kN (nylon with an assumed $E \approx 4$ GPa), Eq. (11) gives a tension rise of about 5–6% at $x = 1$ cm and 18–24% at $x = 2$ cm.

Two consequences follow. First, k_s **risks roughly in proportion to tension**, so tension is the main lever on string-bed stiffness. Second, at typical deflections the stretch term is a modest correction, so gauge and material (which set EA) affect stiffness less than tension does. Thinner strings help mainly in other ways, discussed in Section 5.5.

Note also that the tension in a strung bed is lower than the machine setting, because tension falls rapidly after stringing and friction at the cross-overs leaves cross strings unevenly tensioned [23].

5.3 Two springs in series: where the energy is stored

The string bed and the shuttle carry the same force F , so each stores energy $F^2/2k_i$. The fractions stored in each are

$$f_s = \frac{k_b}{k_s + k_b}, \quad f_b = \frac{k_s}{k_s + k_b}. \quad (12)$$

If each element returns a fraction e_i^2 of the energy it stores, the collision's overall energy return is approximately

$$e^2 \approx f_s e_s^2 + f_b e_b^2 = \frac{k_b e_s^2 + k_s e_b^2}{k_s + k_b}. \quad (13)$$

Eq. (13) is a quasi-static heuristic, not an exact dynamic result, but it captures the mechanism. Strings return most of their stored energy; the shuttle returns little, because its feathers and skirt deform and absorb energy during impact [11]. Lowering k_s (lower tension) raises f_s , moving energy into the efficient element and raising e . In tennis, the measured order is the same: string bed alone has the highest COR, the ball alone the lowest, and ball on string bed lies in between [16].

The badminton evidence agrees in direction:

- A motor-driven racket hit shuttles faster at lower tension, in the order $22 > 24 > 26 > 28 > 30$ lbf [13].
- A combined experimental and FE study found shuttle speed changes of up to about 10% across 20–34 lbf, with higher tension slower [14].
- Rebound COR fell from 0.54 to 0.37 between 22 and 27 lbf, and thicker strings also gave lower COR [12].

There are limits. At very low tension a large share of energy is lost and rebound falls [14], and nylon multifilament strings are hysteretic: fibres slide and rub, and the friction is lost as heat [17]. With real players the picture is less clean: one study found speed fell with tension for beginners, rose for recreational players and stayed level for experts [15], presumably because players adapt their swing to the feel of the racket.

5.4 Contact time and control

The racket rotates during contact. With $\omega \approx V/(0.555 - 0.09\text{ m}) \approx 110\text{ rad/s}$, it turns through $\omega\tau \approx 0.13\text{ rad}$, or about 7.5° , during a 1.2 ms contact. Since $\tau \propto k^{-1/2}$ from Eq. (9), a softer bed lengthens the contact and increases the face rotation while the shuttle is on the strings; a tighter bed shortens it. Variation in that rotation from stroke to stroke becomes variation in launch angle. This is a plausible physical basis for the common claim that higher tension gives more control, at the cost of a few per cent of speed.

5.5 String gauge

At a fixed machine tension, a thinner string gives a slightly faster shuttle: we estimate of order 1% across the commercial range of $0.61\text{--}0.70\text{ mm}$, comparable to lowering tension by $1\text{--}2\text{ lbf}$. The gain comes mostly from lower string mass, not from a softer string bed; the costs are durability and higher working stress.

Cross-sectional area scales as $A = \pi d_s^2/4$, so going from 0.70 to 0.61 mm removes 24% of the area. Table 5 uses nylon density $\rho \approx 1140\text{ kg/m}^3$, an assumed Young’s modulus $E \approx 4\text{ GPa}$, $T = 107\text{ N}$ (24 lbf) and $L = 0.22\text{ m}$.

Table 5: String properties by gauge at 24 lbf (estimates; E assumed).

Gauge d_s	Area A	Linear density λ	Stress $\sigma = T/A$	Pre-strain T/EA	Pitch f_1
(mm)	(mm ²)	(g/m)	(MPa)		(Hz)
0.61	0.292	0.33	366	9.2%	≈ 1290
0.65	0.332	0.38	322	8.1%	≈ 1210
0.68	0.363	0.41	295	7.4%	≈ 1160
0.70	0.385	0.44	278	7.0%	≈ 1120

The gauge acts through six mechanisms.

1. **String-bed stiffness (small).** Gauge enters Eq. (10) only through the stretch term, via EA . By Eq. (11) the stretch adds $\Delta T/T \approx 5\text{--}6\%$ at $x = 1\text{ cm}$ and $18\text{--}24\%$ at $x = 2\text{ cm}$, the lower figure for the thinner string. A 24% change in that correction changes k_s by only a few per cent. A 70% change in k_s (20 to 34 lbf) produces about 10% in speed (Section 5.3), so a few per cent in k_s is worth a few tenths of a per cent.
2. **Moving string mass and vibration loss (probably the largest).** Linear density $\lambda = \rho A$. A string’s modal mass in its fundamental mode is $\lambda L/2 \approx 0.04\text{--}0.05\text{ g}$. The cork engages roughly $8\text{--}10$ strings, a moving mass $m_{str} \approx 0.3\text{--}0.4\text{ g}$, about 7% of the shuttle’s mass. When the shuttle separates, those strings are still moving at roughly the separation speed $v - V' \approx 38\text{ m/s}$ and ring on. The energy left behind is of order $\frac{1}{2}m_{str}(v - V')^2 \approx 0.25\text{ J}$, about 4% of the 6.2 J collision energy $\frac{1}{2}\mu(V + u)^2$. A 24% lighter string recovers about a quarter of this, worth up to roughly $0.5\text{--}1\%$ in shuttle speed. This is an order-of-magnitude estimate.
3. **Working stress and tension loss.** The machine sets force, not stress. At the same lbf, a 0.61 mm string carries about 30% more stress and pre-strain than a 0.70 mm one. It therefore runs closer to its breaking load and plausibly creeps and loses tension faster, which is consistent with lower maximum tensions recommended for thin strings.

4. **Hitting sound.** Transverse wave speed is $c_w = \sqrt{T/\lambda}$, so the single-string fundamental is

$$f_1 = \frac{c_w}{2L} = \frac{1}{2L} \sqrt{\frac{4T}{\pi \rho d_s^2}} \propto \frac{\sqrt{T}}{d_s}.$$

Thinner strings ring about 15% (2.4 semitones) higher, which players hear as a crisper sound [25]; tension-checking apps rely on the same relation. The woven bed's real modes differ from a single string's, but the scaling holds. Note too that the string period $1/f_1 \approx 0.8$ – 0.9 ms is comparable to the contact time τ , so the quasi-static spring model of Section 5.1 is only approximate.

5. **Aerodynamic drag.** Kwan estimated that the strings and frame contribute most of the racket's drag torque, and suggested thinner strings would reduce drag more than a slimmer shaft [4]. String drag scales with d_s , but drag torque is small compared with the torque needed to accelerate the racket, so the gain in V is probably well under 1%.
6. **Durability and bite.** Strings fail mainly by notching at cross-overs and abrasion; a thinner string has less material to lose and works at higher stress. At the same contact force, a thin string also presses harder into the cork, which may improve grip for slices; this is claimed but not, to my knowledge, measured.

The one direct badminton measurement found that rebound COR falls as string diameter increases at the same tension [12], which agrees in direction. Manufacturer “repulsion” ratings combine gauge with core material, braid and coating, so they do not isolate gauge.

6. Frame and shaft

The frame should be stiff during the 1 ms impact, but shaft flex during the swing can add a few per cent to head speed if the stroke is timed to use it.

6.1 During impact: vibration is a loss

A freely held racket's fundamental bending frequency f_n is about 51–54 Hz [7], a period of roughly 19 ms. That is more than ten times the contact time, so energy put into bending the frame during contact cannot spring back into the shuttle before it leaves; it is lost as vibration. Losses are smallest when the impact is near the node of the fundamental mode, which players may seek out by feel [7]. A stiffer head, and a head shape that keeps the frame stable under off-centre hits, reduce these losses. FE studies suggest isometric (squarer) heads give higher COR than oval or round heads [20]. This is probably what frame-based “repulsion” claims refer to.

6.2 During the swing: shaft kick

The racket bends backwards as the player accelerates it and springs forward just before impact. If impact coincides with the forward recoil, the recoil velocity adds to V :

- Strain-gauge studies estimate that elastic deflection contributes about 4–6% of head speed [5].
- A motion-capture example measured an elastic velocity of 1.6 m/s at impact out of 45 m/s, about 3.7% [6].
- Comparing flexible and rigid conditions, a 2024 study found deflection added 13.2% to head speed in a full smash [9].

Elite players consistently hit “early”, while the shaft is still recovering towards straight [4, 5]. Kwan's thesis concludes that a more flexible racket gives slightly more power but less consistent impacts, and that advanced players tend to prefer stiffer rackets for control [4]. Shaft kick is a property of the swing, not of the collision, and Eq. (5) captures it simply as a larger V .

7. Racket mass, swingweight and impact location

A heavier swingweight lowers racket-head speed but raises effective mass, and the two effects nearly cancel; where on the face the shuttle is struck matters more.

7.1 Sensitivity to effective mass

Differentiating Eq. (5) at fixed V and $u = 0$:

$$\frac{\partial \ln v}{\partial \ln M_e} = \frac{r}{1+r} \approx 0.11. \quad (14)$$

So a 10% increase in effective mass gives only about 1% more exit speed, at the same racket speed. Because the shuttle is so light ($r \approx 0.12$), racket mass matters much less in badminton than in tennis.

7.2 The trade-off with swing speed

Players swing a higher-swingweight racket more slowly. Swing speed is commonly fitted by a power law $V = C/I_s^n$, where C depends on the player. For badminton, n averaged 0.22 ± 0.13 across 20 players [7]; Kwan reported 0.32 [4]; tennis and bat studies find about 0.25–0.31 [4, 18].

A worked example: adding 5 kg cm^2 of swingweight by placing mass at the tip (total mass unchanged) raises I_{cm} by about 10% and, from Eq. (1), M_e at head centre from 42.5 g to about 44.5 g. By Eq. (14) that adds about 0.5% to v . Meanwhile measured head speed falls by about 0.7 m/s, or 1.3% [7]. The net change at a fixed impact point is about -0.8% . Players also tend to strike slightly closer to the tip with higher-swingweight rackets, where the face moves faster [7], which recovers some of the difference.

The measurements agree: across five rackets from 85 to 106 kg cm^2 , head speed fell significantly but shuttle speed showed no significant change [7]. Kwan’s model, with impact location held fixed, predicts a slight fall in shuttle speed with swingweight, so a very head-heavy racket does not give more power [4].

7.3 Is the racket the right mass?

Cross’s double-pendulum analysis suggests that energy transfer from arm to ball is most efficient when the implement’s mass is near the geometric mean of the arm’s and the ball’s [3]. For an arm of about 1850 g and a 5 g shuttle that mean is $\sqrt{1850 \times 5} \approx 96 \text{ g}$, and the mass ratios are about 19 at each step [4]. Modern rackets already sit at this optimum.

7.4 Impact location

In 2386 smashes by 65 international players, impact location explained about 26% of the variation in each player’s shuttle speed. Impacts within one SD of the mean location cost up to 5.3% of the player’s best speed [8]. Eq. (1) shows why: moving the impact 5 cm towards the tip cuts M_e from 42 to 35 g, and the small polar MoI means a hit 4 cm off-axis cuts it to 31 g (Table 2), before adding any vibration and twisting losses.

8. Towards a definition of “repulsion”

“Repulsion” is best read as the coefficient of restitution of the strung racket, and of the string bed within it; the word is a direct translation of the Japanese 反発 (*hanpatsu*), as in 反発係数, the standard Japanese term for COR.

Yonex rates its strings from 1 to 10 for repulsion power, durability, shock absorption, control and hitting sound (BG66 Ultimax, for example, scores 10 for repulsion and 6 for durability [24]), but publishes no test method. Retailer guides describe repulsion as how much the string helps push the shuttle away, and note that it tends to fall as durability and tension rise [22]. Golf offers a precedent for a formal definition: the governing bodies limit drivers to a COR of 0.830, and Japanese marketing calls clubs above it 高反発, “high repulsion”.

In the terms of this note, three definitions are defensible:

1. **Racket repulsion at a point on the face:** the ACOR e_A of Eq. (6), measured by firing a shuttle at a stationary, freely suspended racket; equivalently the “rebound power” $\partial v/\partial V = (1+e)/(1+r)$ from Eq. (5). It combines string-bed energy return, frame vibration loss and effective mass, and can be mapped across the face to show the sweet spot.
2. **String repulsion:** a low string-bed stiffness k_s (set mainly by tension, and to a lesser extent by gauge and material) together with a high intrinsic energy return e_s^2 (low hysteresis and low friction between strings) and low moving string mass. By Eq. (13), low k_s keeps energy out of the shuttle, and high e_s means the strings give back what they store. This explains why thin gauges, lower tensions and smooth coatings all carry the “high repulsion” label, and why repulsion trades off against durability and control.
3. **Colloquial usage**, which often also covers shaft kick (Section 6.2). That acts before impact through V , and is not a property of the collision.

On scale: string choices are second-order effects compared with racket-head speed and timing. Even in tennis, tension and string material change ball speed only a little while changing feel much more [16].

9. Summary: what changes shuttle speed, and which way

Racket-head speed dominates; every equipment effect is a few per cent, and increasing string tension reduces shuttle speed (Table 6).

Table 6: Effect on shuttle speed of increasing each quantity, for the smash conditions of Section 2. Sizes are indicative; players adjust their swing and impact point to the racket they hold.

Increasing...	Effect on shuttle speed	Approximate size	Basis
Racket-head speed V	Faster	Proportional (1:1)	Eq. (5)
Shaft flexibility, with well-timed impact	Faster (less consistent)	+4–6% of head speed; up to 13% in one study	[5, 9]
String tension T	Slower	Up to $\approx 10\%$ slower from 20 to 34 lbf (machine tests); varies with skill in human tests	[13, 14, 15]
Distance of impact from the sweet spot	Slower	Up to 5.3% slower within one SD of a player’s mean impact point	[8]
Coefficient of restitution e	Faster	+0.05 in e gives $\approx +3\%$	Eq. (5)
String gauge (diameter) d_s	Slower	Small: $\approx 1\%$ faster from 0.70 to 0.61 mm (estimate, Section 5.5)	[12], §5.5
Effective mass M_e , at the same racket speed	Faster	+10% gives $\approx +1\%$	Eq. (14)
Swingweight I_s , as actually swung	No significant change	Head speed -0.7 m/s per $+5$ kg cm ² , offset by higher M_e	[7]
Incoming shuttle speed u	Faster	Adds $e_A u \approx 0.5u$	Eq. (5)

Note on sources

Equations (1)–(9) are standard rigid-body and impact mechanics; Equations (10)–(13) and the gauge estimates of Section 5.5 are the author’s simplified models. Worked numbers use the representative values of Section 2.

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