The Millisecond Physics of a Soccer Kick: Derivation, Physical Intuition, Nonlinear Contact, and Computational Experiments

Computational study with reproducible Python simulations

July 16, 2026

Abstract

The visible flight of a soccer ball begins with a much shorter and more mechanically subtle event: the few milliseconds during which the foot and ball deform one another. This paper derives a reduced model of that contact phase from Newton's laws, momentum balance, relative motion, constitutive contact mechanics, and energy bookkeeping. The foot is represented by a contact-point effective mass, the ball by a translational mass with nonlinear compliance, and the interaction by a nonlinear spring–damper law. The derivation explains why the foot and ball momentarily have the same normal velocity at maximum compression, why the ball can subsequently separate with a speed greater than the foot speed, and why this does not violate conservation of momentum or energy. The model also clarifies the distinct roles of effective impact mass, stiffness, damping, initial relative velocity, and active drive during contact. Numerical simulations reveal several non-obvious results: stiffness can strongly increase peak force while changing ball exit speed only modestly; strong damping can raise the measured peak force while reducing useful rebound; effective impact mass has diminishing returns; and forceful muscle action during the contact interval contributes less than might be expected because the interval is extremely short. The paper emphasizes both the value and the limits of the reduced model. The governing conservation laws are simple, but identifying the correct effective parameters for a deformable, rotating, articulated human–ball system is a genuinely complex inverse and multiscale problem.

Contents

1 The physical question

A soccer kick is often introduced as a projectile-motion problem. That treatment begins after the ball has already left the foot. The present paper focuses instead on the launch mechanism itself: the foot–ball contact interval.

The central puzzle is simple to state:

> How can a soccer ball leave the foot with a speed greater than the speed of the foot immediately before impact?

The answer is not that the foot drags the ball continuously, and not that kinetic energy appears from nowhere. During impact, the ball deforms. The foot first does work on this deformation, temporarily storing energy. The deformed ball then recovers its shape and continues to push on both bodies. Because the ball is much lighter than the effective moving portion of the leg, a moderate transfer of momentum can generate a large ball velocity.

The contact process has three stages:

1. **Compression:** the foot is faster than the ball and closes the gap.
2. **Maximum compression:** the relative normal velocity is momentarily zero.
3. **Restitution:** the ball re-expands, accelerates further, and separates from the foot.

The conservation laws are straightforward. The difficulty lies in representing the deformable ball, the shoe, the articulated leg, and the evolving contact geometry with parameters that are both physically meaningful and measurable.

2 A hierarchy of models

It is useful to distinguish three descriptions of the same event.

2.1 Impulse-only model

The shortest possible model ignores the force history and keeps only the total impulse,

$$J = \int_{t_0}^{t_1} F_c(t)\, dt. \tag{1}$$

For the ball,

$$m_b \left(v_b^+ - v_b^- \right) = J. \tag{2}$$

This model predicts the velocity change if the impulse is known, but it does not explain where the impulse comes from, how large the ball compression becomes, how long contact lasts, or how the force varies in time.

2.2 Rigid-body collision model

A second model treats the foot and ball as rigid bodies and introduces a coefficient of restitution. This gives closed-form exit velocities and useful scaling intuition, but still suppresses the deformation history.

2.3 Time-resolved compliant contact model

The model developed here explicitly resolves deformation, force, velocity, impulse, and energy over time. It is still reduced to one dimension, but it contains the minimum structure needed to represent compression and restitution as distinct physical phases.

3 Coordinates and kinematics

Let $x_f(t)$ be the position of the effective foot contact point and $x_b(t)$ the position of the ball surface coordinate represented along the local contact normal. Their velocities are

$$v_f = \dot{x}_f, \qquad v_b = \dot{x}_b. \tag{3}$$

We choose the positive direction from the foot toward the ball.

The relative approach velocity is

$$v_{\text{rel}} = v_f - v_b. \tag{4}$$

If $v_{\text{rel}} > 0$, the foot is gaining on the ball. If $v_{\text{rel}} < 0$, the ball is moving away from the foot faster than the foot can follow.

The compression coordinate is defined by

$$\delta(t) = \max\left(0, x_f - x_b\right). \tag{5}$$

Differentiating while contact exists gives

$$\dot{\delta} = v_f - v_b = v_{\text{rel}}. \tag{6}$$

Equation (6) is the kinematic heart of the problem. It immediately identifies the physical phases:

$$\dot{\delta} > 0 \quad \text{compression}, \tag{7}$$

$$\dot{\delta} = 0 \quad \text{maximum compression}, \tag{8}$$

$$\dot{\delta} < 0 \quad \text{restitution}. \tag{9}$$

At maximum compression,

$$v_f = v_b. \tag{10}$$

This equality is instantaneous. It does not imply that the foot and ball remain attached. Immediately afterward, the stored elastic energy causes the ball to accelerate away.

4 Why the foot is represented by an effective mass

The anatomical foot is not an isolated rigid block. It is connected to the lower leg, thigh, pelvis, and torso through joints. A force applied at the shoe therefore produces an acceleration that depends on the configuration and inertia of the entire articulated system.

For a point moving along the impact normal $\boldsymbol{n}$, the effective mass can be written formally as

$$m_{\text{eff}} = \left(\boldsymbol{n}^T J M^{-1} J^T \boldsymbol{n}\right)^{-1}, \tag{11}$$

where M is the generalized mass matrix and J maps generalized velocities to contact-point velocity.

Equation (11) should be read as follows. The same external contact force can produce a large or small foot-point acceleration depending on joint configuration. If the leg is mechanically well coupled and difficult to decelerate along the impact direction, the contact point behaves as though it has a relatively large mass. If the ankle or knee yields easily, the contact point behaves as though it has a smaller mass.

This is not a literal statement that several kilograms of body tissue are concentrated in the foot. It is a statement about the ratio

$$m_{\text{eff}} \sim \frac{\text{contact force}}{\text{foot-point acceleration}}. \tag{12}$$

In the reduced model, we denote this scalar by m_f.

5 Deriving the equations of motion

Let F_c be the compressive contact force exerted by the foot on the ball. By Newton's third law, the ball exerts the equal and opposite force $-F_c$ on the foot.

For the effective foot mass,

$$m_f \ddot{x}_f = F_{\text{drive}} - F_c. \tag{13}$$

For the ball,

$$m_b \ddot{x}_b = F_c. \tag{14}$$

The optional term F_{drive} represents an external generalized force transmitted through the leg during contact. It is zero for a passive collision.

Equations (13)–(14) already provide useful intuition:

- the same contact force decelerates the foot and accelerates the ball;
- because $m_b \ll m_f$, the ball acceleration is usually much larger;
- the ball can therefore gain velocity faster than the foot loses velocity.

Subtracting the two equations gives an equation for the compression coordinate:

$$\ddot{\delta} = \ddot{x}_f - \ddot{x}_b \tag{15}$$

$$= \frac{F_{\text{drive}}}{m_f} - F_c \left(\frac{1}{m_f} + \frac{1}{m_b} \right). \tag{16}$$

Define the reduced mass

$$\mu = \frac{m_f m_b}{m_f + m_b}. \tag{17}$$

Then

$$\mu \ddot{\delta} = \frac{\mu}{m_f} F_{\text{drive}} - F_c. \tag{18}$$

This equation reveals an important simplification: the internal deformation evolves as if a single reduced mass μ were compressing the contact element.

When $m_f \gg m_b$,

$$\mu \approx m_b. \tag{19}$$

In that regime, increasing the effective foot mass further has little effect on the deformation dynamics. This is the mathematical origin of diminishing returns.

6 Constitutive law for the deforming ball

Newton's laws do not determine the contact force by themselves. A constitutive law is needed to connect force with deformation and deformation rate.

We use

$$F_c(\delta, \dot{\delta}) = \begin{cases} k\delta^n + c \max(\dot{\delta}, 0), & \delta > 0, \\ 0, & \delta \le 0. \end{cases} \tag{20}$$

6.1 Elastic term

The term

$$F_e = k\delta^n \tag{21}$$

represents recoverable deformation. For $n = 1$, it reduces to a linear spring. For $n > 1$, the contact stiffens as compression grows. This is physically plausible because a pressurized spherical shell becomes progressively harder to flatten as the contact patch expands and membrane tension increases.

The corresponding elastic potential energy follows from

$$U(\delta) = \int_0^{\delta} F_e(s)\, ds, \tag{22}$$

which gives

$$U(\delta) = \frac{k}{n+1}\delta^{n+1}. \tag{23}$$

This derivation is important: the ball is able to leave faster than the foot because energy stored in U during compression is released during restitution.

6.2 Damping term

The term

$$F_d = c \max(\dot{\delta}, 0) \tag{24}$$

represents irreversible loss during compression. It is a phenomenological approximation for material hysteresis, shoe deformation, internal vibration, heat, and sound.

The associated instantaneous dissipation rate during compression is approximately

$$P_{\text{diss}} = F_d \dot{\delta} = c\dot{\delta}^2 \geq 0. \tag{25}$$

Thus damping can never create mechanical energy. It converts organized translational and elastic energy into unmodeled internal modes.

The compression-only damping convention is deliberately simple. A more realistic viscoelastic law would generally be nonlinear and could act during both loading and unloading while preserving non-negative net dissipation over a full cycle.

7 Momentum balance and center-of-mass motion

Adding Eqs. (13) and (14) gives

$$\frac{d}{dt}\left(m_f v_f + m_b v_b\right) = F_{\text{drive}}. \tag{26}$$

For $F_{\text{drive}} = 0$, total momentum is conserved:

$$m_f v_f + m_b v_b = P_0. \tag{27}$$

The center-of-mass velocity is therefore constant,

$$V_{\text{cm}} = \frac{m_f v_f + m_b v_b}{m_f + m_b}. \tag{28}$$

At maximum compression, $v_f = v_b = v_*$, so momentum conservation gives

$$v_* = V_{\text{cm}} = \frac{m_f v_f^- + m_b v_b^-}{m_f + m_b}. \tag{29}$$

This is a useful result. At maximum compression, both bodies move together at the center-of-mass velocity. The relative kinetic energy has been converted into elastic energy and dissipation.

8 Energy decomposition

The total translational kinetic energy is

$$K = \frac{1}{2} m_f v_f^2 + \frac{1}{2} m_b v_b^2. \tag{30}$$

It can be decomposed exactly into center-of-mass and relative parts:

$$K = \frac{1}{2}(m_f + m_b) V_{\rm cm}^2 + \frac{1}{2}\mu (v_f - v_b)^2. \tag{31}$$

The first term cannot be changed by internal contact forces. Only the relative kinetic energy

$$K_{\rm rel} = \frac{1}{2}\mu v_{\rm rel}^2 \tag{32}$$

is available for conversion into deformation and dissipation.

At maximum compression, $v_{\rm rel} = 0$, so the relative kinetic energy has vanished. In the undamped passive case,

$$U(\delta_{\max}) = \frac{1}{2}\mu (v_f^- - v_b^-)^2. \tag{33}$$

Combining Eq. (23) with Eq. (33) gives the scaling estimate

$$\delta_{\max} \sim \left[\frac{(n+1)\mu (v_f^- - v_b^-)^2}{2k} \right]^{1/(n+1)}. \tag{34}$$

This predicts that maximum compression increases with relative speed and reduced mass, but decreases with stiffness.

Substituting Eq. (34) into $F_{\max} \sim k\delta_{\max}^n$ gives

$$F_{\max} \sim k^{1/(n+1)} \left[\mu (v_f^- - v_b^-)^2 \right]^{n/(n+1)}. \tag{35}$$

The physical message is subtle: increasing stiffness raises peak force, but sublinearly. At the same time it reduces compression and contact duration.

9 Why the ball can leave faster than the foot

The simplest demonstration uses the coefficient of restitution e, defined by

$$v_b^+ - v_f^+ = e\left(v_f^- - v_b^-\right). \tag{36}$$

Together with momentum conservation, this gives

$$v_b^+ = \frac{(1+e)m_f}{m_f + m_b} v_f^- + \frac{m_b - e m_f}{m_f + m_b} v_b^-. \tag{37}$$

For an initially stationary ball,

$$\frac{v_b^+}{v_f^-} = \frac{(1+e)m_f}{m_f + m_b}. \tag{38}$$

The ratio exceeds unity when

$$e > \frac{m_b}{m_f}. \tag{39}$$

For $m_f = 3\,\mathrm{kg}$ and $m_b = 0.43\,\mathrm{kg}$, the threshold is only about 0.143. Therefore even a moderately restitutive collision can launch the ball faster than the incoming foot.

In the elastic limit $e = 1$ and for $m_f \gg m_b$,

$$v_b^+ \to 2v_f^-. \tag{40}$$

This does not violate energy conservation. A massive moving object can transfer energy to a much lighter object, giving the lighter object a larger speed while the heavier object loses only a smaller fraction of its own speed.

10 Characteristic timescale

For a linear undamped contact law ($n = 1$, $c = 0$), the relative equation becomes

$$\mu\ddot{\delta} + k\delta = 0. \tag{41}$$

Its angular frequency is

$$\omega_0 = \sqrt{\frac{k}{\mu}}. \tag{42}$$

Starting from zero compression and positive approach speed, separation occurs after approximately half an oscillation:

$$t_c \approx \pi\sqrt{\frac{\mu}{k}}. \tag{43}$$

This gives the main scaling intuition:

- larger stiffness shortens contact;
- larger reduced mass lengthens contact;
- the millisecond timescale follows naturally from the large stiffness of the ball–shoe system.

For nonlinear contact, the duration also depends on impact speed because the effective tangent stiffness changes with compression.

11 Dimensionless interpretation

The problem can be organized around a few ratios.

11.1 Mass ratio

$$r = \frac{m_f}{m_b}. \tag{44}$$

Large r means the foot is difficult for the ball to decelerate. The exit-speed ratio approaches a finite limit as $r \to \infty$.

11.2 Relative-speed scale

The mechanically relevant incoming velocity is

$$V_0 = v_f^- - v_b^-. \tag{45}$$

A moving ball can therefore radically change the impact even when the foot speed is unchanged.

11.3 Damping strength

For a linearized model, a useful damping ratio is

$$\zeta = \frac{c}{2\sqrt{k\mu}}. \tag{46}$$

Small ζ corresponds to a nearly elastic event; large ζ corresponds to strong dissipation. In the nonlinear model this is only a local guide because the effective stiffness varies with δ.

12 Numerical method

The state vector is

$$\boldsymbol{y} = (x_f, v_f, x_b, v_b)^T. \tag{47}$$

Equations (13)–(14) are integrated with a fourth-order Runge–Kutta method using a time step of 5 µs. The step is much smaller than the millisecond contact duration, allowing the force peak and the velocity crossing to be resolved.

Contact begins at zero compression with $v_f > v_b$. The simulation ends at the first time after compression for which

$$\delta \leq 0, \qquad v_b \geq v_f. \tag{48}$$

The second condition prevents an unphysical termination while the foot is still catching the ball.

The baseline parameters are shown in Table 1.

Table 1: Baseline parameters. The stiffness units depend on the nonlinear exponent and are therefore reported as model units.

Parameter	Symbol	Value
Effective impact mass	m_f	3.0 kg
Ball mass	m_b	0.43 kg
Initial foot speed	v_f^-	22 m/s
Initial ball speed	v_b^-	0 m/s
Stiffness coefficient	k	4.2×10^5 model units
Damping coefficient	c	120 N s/m
Nonlinearity exponent	n	1.35
Drive force	F_{drive}	0 N
Time step	Δt	5 µs

13 Baseline dynamics

The baseline simulation gives approximately

$$v_b^+ = 31.98\,\text{m/s}, \tag{49}$$
$$v_f^+ = 17.42\,\text{m/s}, \tag{50}$$
$$t_c = 5.29\,\text{ms}, \tag{51}$$
$$F_{\max} = 3.80\,\text{kN}, \tag{52}$$
$$\delta_{\max} = 27.9\,\text{mm}. \tag{53}$$

Figure 1 displays force, velocities, compression, and energy.

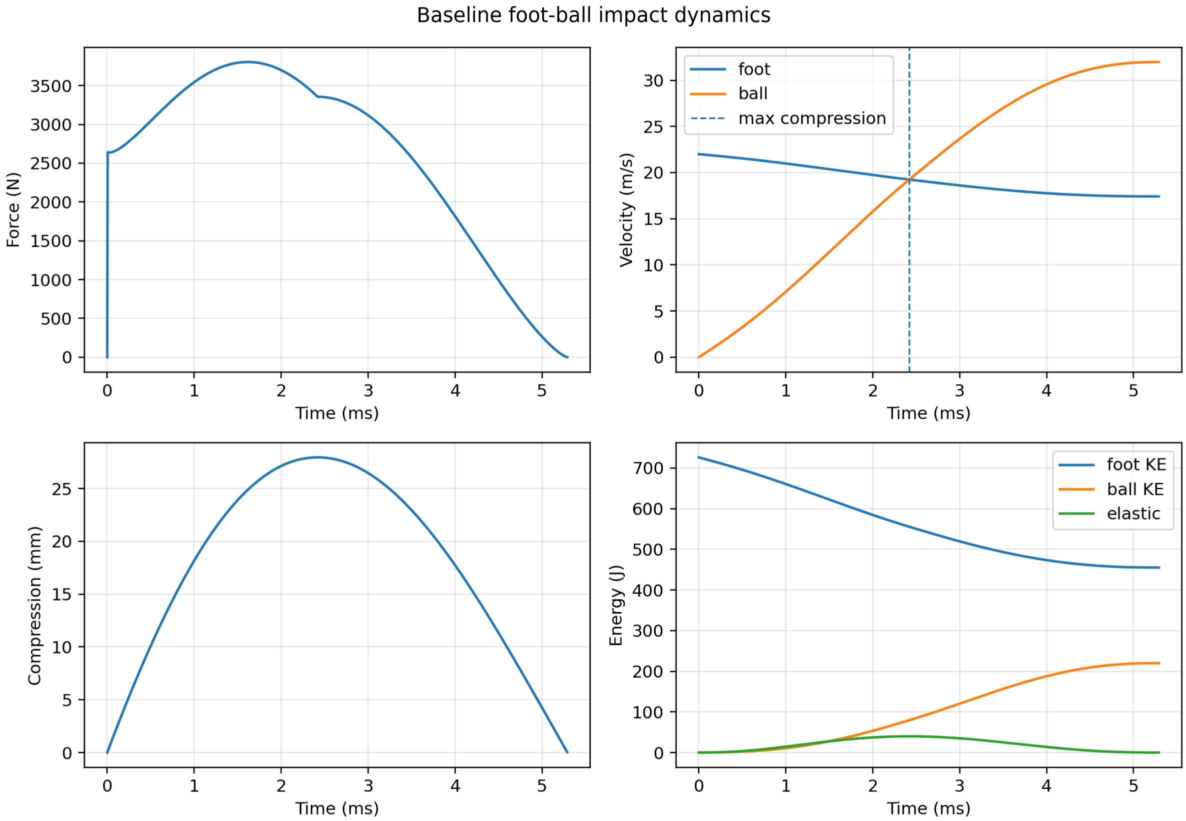

Figure 1: Baseline time history. The velocity curves cross at maximum compression. Before that crossing, the foot is compressing the ball. After it, the ball is re-expanding and moving faster than the foot. The elastic-energy curve peaks close to maximum compression.

The energy plot should not be interpreted as a perfectly closed budget because the damping term transfers energy into unmodeled internal modes. The missing mechanical energy is the model's representation of heat, vibration, sound, and material hysteresis.

14 Scenario studies and physical interpretation

14.1 Effective impact mass: why the gains saturate

Figure 2 shows the exit-speed ratio as effective impact mass increases.

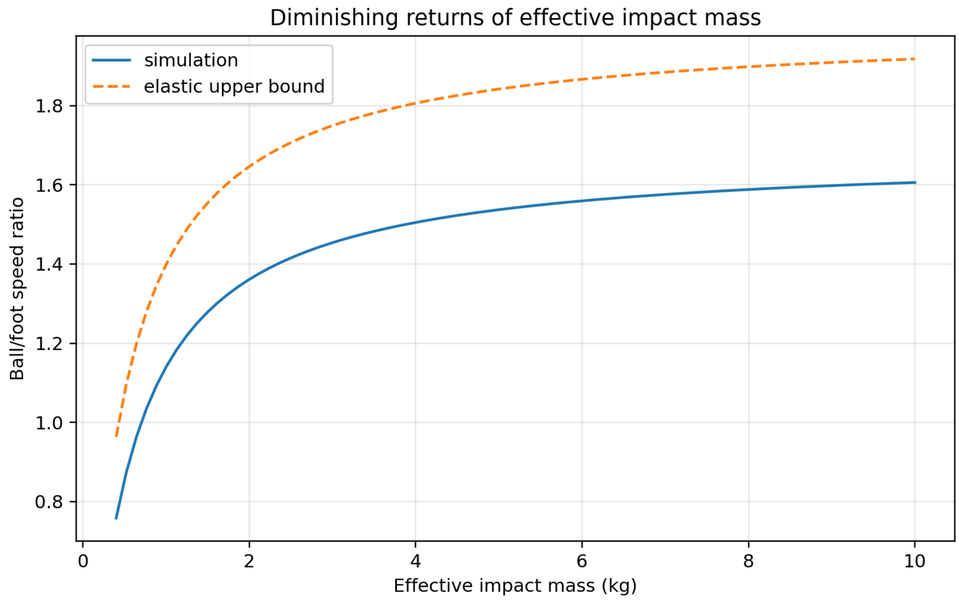

Figure 2: Ball-to-foot speed ratio versus effective impact mass. The dashed curve is the perfectly elastic upper bound. The flattening arises because the reduced mass approaches the ball mass and the foot increasingly resembles a moving wall.

When m_f is small, the reaction force from the ball strongly decelerates the foot. Increasing mechanical coupling can then make a large difference. When $m_f \gg m_b$, however, the foot already behaves almost like an infinitely massive moving boundary. Additional mass produces only a small improvement.

This explains why "locking" the ankle may improve performance up to a point but cannot increase ball speed without bound. The dominant benefit of technique is often to create high foot speed before contact and avoid losing effective mass through compliant joint motion.

14.2 Stiffness: peak force is not impulse

Figure 3 shows that stiffness has a dramatic effect on force and duration, but a weaker effect on exit speed.

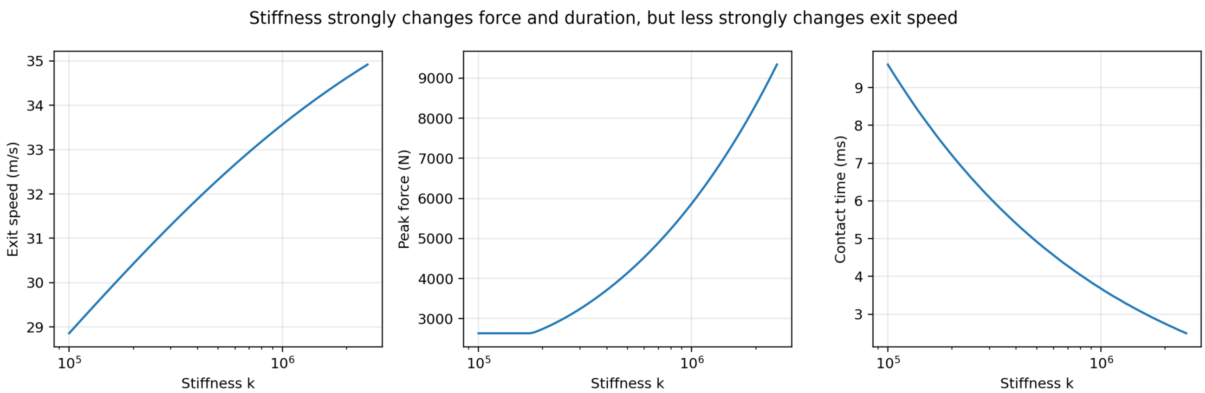

Figure 3: Stiffness sweep. A stiffer system creates a shorter, sharper impact. Peak force changes strongly, but exit speed changes much less because ball momentum depends on the area under the force–time curve.

Impulse is

$$J = \int F_c(t)\, dt. \tag{54}$$

A narrow high peak can have nearly the same area as a broad lower peak. Consequently, peak force is not a reliable measure of performance by itself. It may be more relevant to injury risk, local pressure, shoe comfort, or material failure than to ball exit speed.

The unexpected result is that a harder-feeling impact may deliver only a modest increase in useful momentum transfer.

14.3 Damping: a large force can accompany poor rebound

Figure 4 shows the effect of increasing damping.

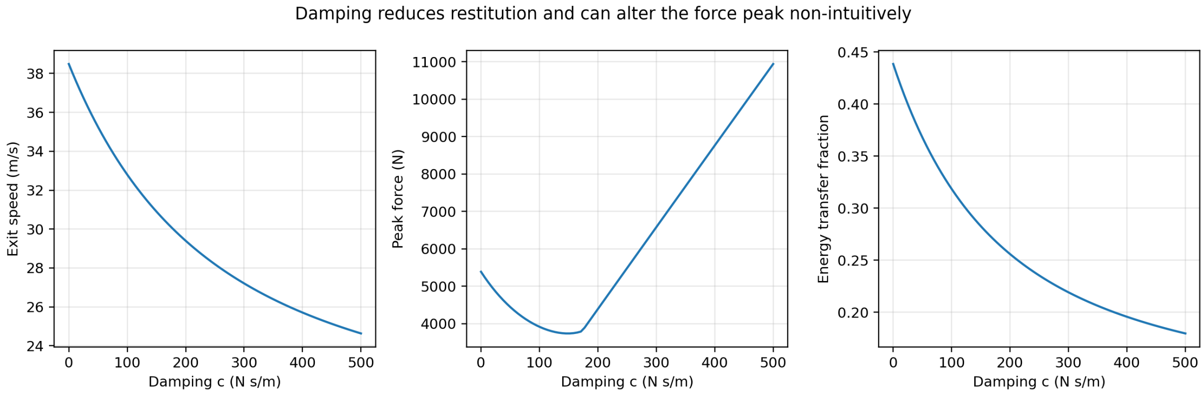

Figure 4: Damping sweep. Greater damping removes energy from the restitution phase and lowers ball exit speed. Because the damping term also contributes directly to force during compression, peak force can increase even while useful rebound decreases.

This is an important warning for experiments. A sensor may record a high force peak in a highly dissipative impact. That does not mean the impact is efficient. High peak force and high energy transfer are different properties.

14.4 Active foot drive: why "follow through" is mostly prepared before impact

The active drive force contributes an impulse of order

$$J_{\text{drive}} \sim F_{\text{drive}} t_c. \tag{55}$$

Even a force of 1000 N acting for 5 ms gives only about 5 N s. Moreover, that impulse acts on the foot–ball system and is not transferred entirely to the ball.

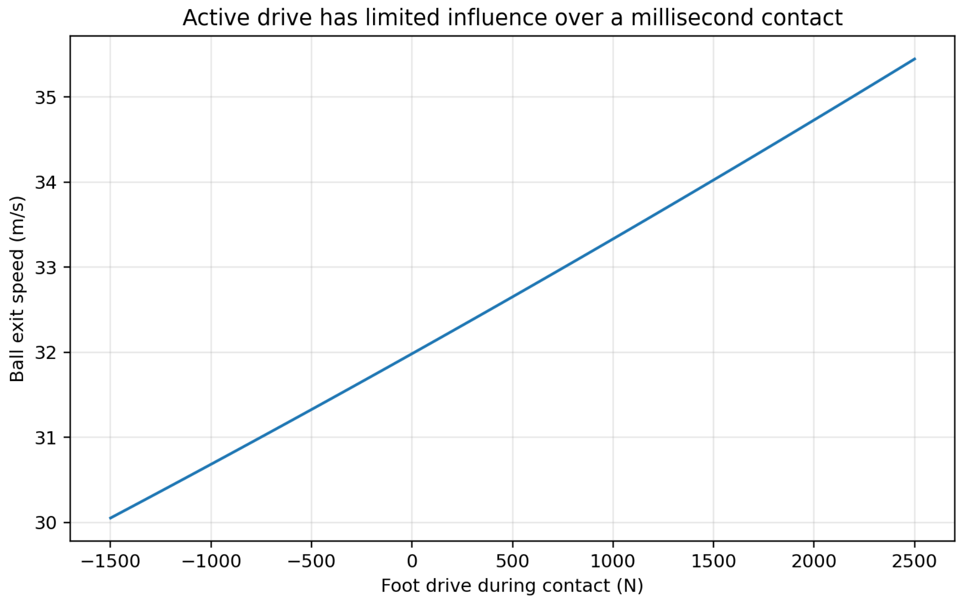

Figure 5: Effect of an imposed drive force during contact. The influence is real but limited because the contact interval is extremely short.

The conclusion is not that follow-through is irrelevant. Rather, its largest mechanical contributions occur before contact: producing foot speed, selecting impact direction, and configuring the joints so that the effective mass is favorable. The visible continuation of the leg after impact is partly a consequence of the pre-impact motion rather than a long push on the ball.

14.5 Initial ball velocity: relative motion controls severity

Figure 6 varies the initial ball velocity while holding foot speed fixed.

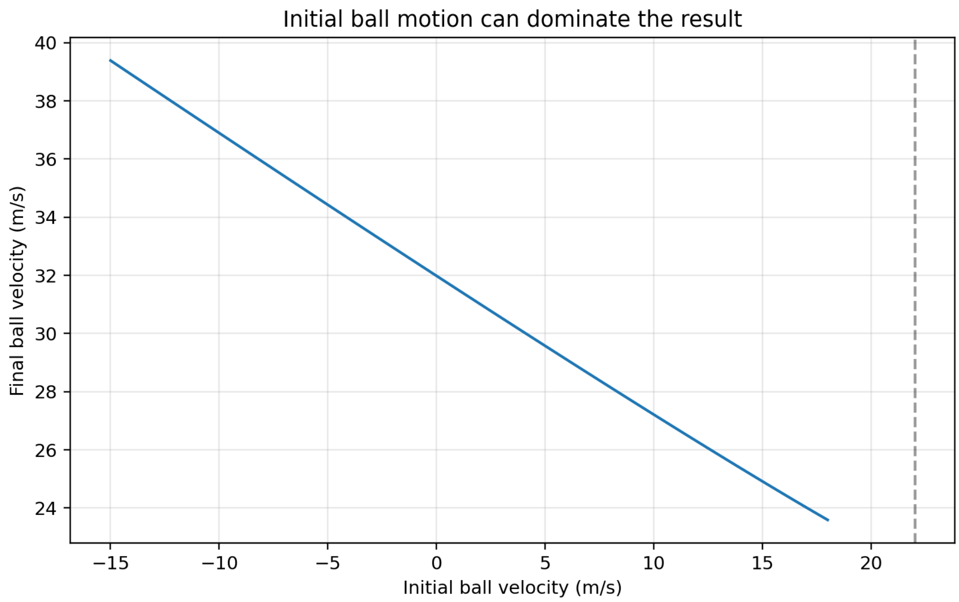

Figure 6: Final ball velocity versus initial ball velocity. A ball moving toward the foot increases the relative speed and the available relative kinetic energy. A ball already moving in the kick direction reduces both.

The relevant energy scale is

$$K_{\text{rel}}^{-} = \frac{1}{2}\mu(v_f^{-} - v_b^{-})^2. \tag{56}$$

Thus the same foot speed can produce very different force, compression, and exit speed depending on the ball's incoming motion.

15 Concrete and extreme cases

Table 2 compares representative model scenarios.

Table 2: Representative numerical scenarios. These values illustrate mechanisms rather than provide calibrated predictions for a specific player or ball.

Scenario	v_b^+ (m/s)	Ratio	Peak force (N)	Contact (ms)	Compression (mm)
Baseline	31.98	1.45	3804	5.29	27.95
Light effective foot	20.55	0.93	2962	4.43	21.71
Heavy effective foot	34.94	1.59	4014	5.48	29.35
Very soft ball	29.28	1.33	2637	8.91	38.87
Very stiff ball	34.47	1.57	7905	2.87	17.51
Highly damped	25.13	1.14	9853	5.10	14.49
Ball approaching foot	35.90	1.63	5469	5.05	36.90
Ball already moving	27.21	1.24	1876	5.78	16.20

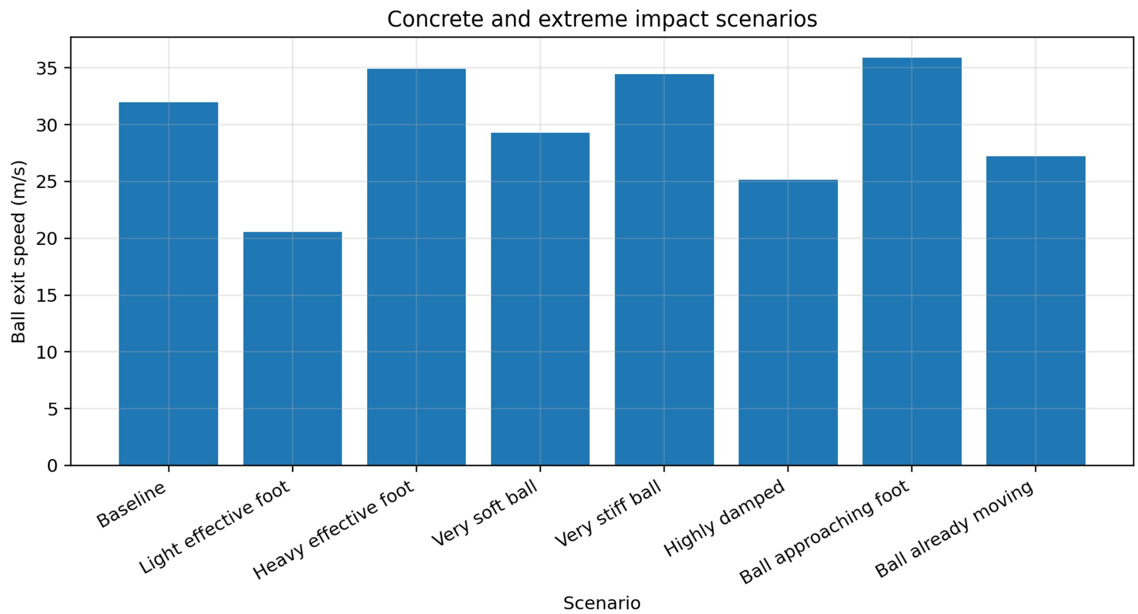

Figure 7: Ball exit speed for selected baseline and extreme scenarios.

The most interesting cases are:

1. **Light effective foot.** The foot is strongly decelerated and the ball leaves slower than the incoming foot. A fast-looking swing is not sufficient if the contact-point inertia is low.

2. **Very stiff ball.** Peak force nearly doubles relative to baseline, but exit speed rises only moderately. Force magnitude and momentum transfer are not interchangeable.

3. **Highly damped contact.** This case produces the largest peak force in the table yet a relatively low ball speed. A violent force pulse can be mechanically inefficient.

4. **Approaching ball.** The incoming ball increases relative speed and therefore increases both deformation energy and possible outgoing speed.

16 Extreme analytical limits

16.1 Infinitely heavy foot

As $m_f/m_b \to \infty$, the foot speed is nearly unchanged by impact. In the restitution model,

$$v_b^+ \to (1+e)v_f^- - ev_b^-. \tag{57}$$

For a stationary ball and $e = 1$, this gives $v_b^+ = 2v_f^-$. The foot behaves like a moving wall.

16.2 Vanishing effective foot mass

As $m_f \to 0$, the foot has little momentum and is easily stopped. For a stationary ball,

$$v_b^+ \to 0. \tag{58}$$

Large foot speed alone is not enough; momentum and effective inertia matter.

16.3 Perfectly inelastic collision

For $e = 0$, foot and ball leave with the same velocity,

$$v_f^+ = v_b^+ = V_{\mathrm{cm}}. \tag{59}$$

There is no restitution phase capable of accelerating the ball beyond the foot.

16.4 Perfectly elastic collision

For $e = 1$, relative speed reverses without loss,

$$v_b^+ - v_f^+ = v_f^- - v_b^-. \tag{60}$$

This is the maximum-speed passive collision allowed by the two-mass rigid-body model.

16.5 Infinite stiffness

As $k \to \infty$, compression and contact duration tend toward zero while peak force tends to become very large. The finite impulse can remain well defined. This limit approaches an instantaneous rigid-body collision and illustrates why force peaks are numerically and experimentally delicate.

16.6 Zero stiffness

As $k \to 0$, the interaction becomes extremely soft and long. The ball deforms greatly, and a finite-duration model may no longer represent a realistic soccer ball. Gravity, geometry, and large-deformation shell mechanics would become important.

17 Why the real problem is genuinely complex

The reduced equations are compact, but each parameter hides substantial physics.

17.1 The contact-point mass is configuration dependent

The effective mass depends on joint angles, segment inertias, muscle co-contraction, and impact direction. It may also change during the contact interval. Treating it as constant is a strong reduction.

17.2 The ball is a pressurized shell, not a point spring

A soccer ball contains a flexible shell, seams, panels, internal gas, and a growing contact patch. Membrane tension, bending, local buckling, internal pressure redistribution, and wave propagation all contribute to the force law.

17.3 The shoe and soft tissue deform

The measured compliance is not the ball alone. Shoe upper, sole, foot soft tissue, and possibly the ankle all deform. The fitted stiffness is therefore a system property.

17.4 Contact is three-dimensional

Real impacts are rarely central. Tangential contact forces generate spin. The line of action changes as the ball and shoe deform. Friction may alternate between sticking and sliding.

17.5 Rotation couples to translation

An off-center impulse $\boldsymbol{J}$ applied at position $\boldsymbol{r}$ gives angular impulse

$$\Delta \boldsymbol{L} = \boldsymbol{r} \times \boldsymbol{J}. \tag{61}$$

The same contact event therefore partitions energy between translational speed and spin. A one-dimensional model cannot predict this partition.

17.6 Material behavior is rate dependent

The apparent stiffness and damping can depend on impact speed, temperature, inflation pressure, previous loading, and manufacturing construction. A single k, c, and n may not transfer across conditions.

17.7 Muscle and tendon dynamics are not instantaneous

Muscles generate force through activation and contraction dynamics; tendons store and release energy; joints have impedance rather than fixed stiffness. The player cannot arbitrarily prescribe a constant drive force over a few milliseconds.

17.8 The inverse problem is underdetermined

Measuring only ball exit speed does not uniquely identify effective mass, stiffness, damping, or drive. Different parameter combinations can produce similar final velocities but different force histories. Reliable identification requires synchronized measurements of foot speed, ball deformation, contact duration, and ideally contact force or pressure.

18 Assumptions and approximations

The model assumes:

1. one-dimensional central impact;

2. constant effective foot mass;

3. no foot or ball rotation;

4. no tangential friction;

5. negligible gravity during the few-millisecond contact;

6. a single nonlinear compliance coordinate;
7. a phenomenological damping law;
8. constant model parameters during impact;
9. no distributed wave propagation in the ball or leg;
10. no explicit internal air dynamics.

These assumptions are appropriate for explaining the basic mechanism but not for predicting a specific professional kick to engineering accuracy.

19 Validation strategy for a more realistic model

A useful experimental program would combine:

- high-speed video to measure foot and ball velocity;
- marker-based or markerless motion capture to estimate joint configuration;
- ball deformation imaging to estimate $\delta(t)$;
- instrumented shoe or pressure film to estimate force distribution;
- repeated trials at different inflation pressures and approach speeds;
- inverse fitting of m_f, k, c, and n to full time histories rather than exit speed alone.

The most informative quantities are not only final speed but also contact duration, maximum compression, velocity crossing time, force impulse, and energy loss.

20 Conclusions

The foot–ball impact is simple at the level of conservation laws and complex at the level of constitutive and biomechanical detail. The key physical mechanism is a temporary conversion of relative kinetic energy into deformation energy, followed by partial release during restitution. At maximum compression, foot and ball share the center-of-mass velocity. During restitution, the lighter ball accelerates beyond the foot and separates.

The main conclusions are:

- ball speed is controlled by relative velocity, effective impact mass, and restitution, not foot speed alone;
- effective impact mass has diminishing returns because the reduced mass approaches the ball mass;
- stiffness controls the shape and peak of the force pulse more strongly than it controls total impulse;
- damping can increase peak force while reducing useful energy return;
- active drive during contact is limited by the millisecond duration, although pre-impact muscle action is essential;
- high peak force is not equivalent to an efficient kick;
- realistic prediction requires a coupled multibody, deformable-contact, and rotational model with experimentally identified parameters.

The apparent simplicity of a kick therefore hides a multiscale problem: rigid-body momentum exchange occurs together with nonlinear shell deformation, viscoelastic loss, joint impedance, and changing geometry over only a few thousandths of a second.

Reproducibility

The accompanying Python script `simulate_kick.py` generates the figures and scenario table. It uses NumPy and Matplotlib. The model is intended to be transparent enough for modification, sensitivity analysis, and extension to rotational or multibody dynamics.