Commentary

Why the Mid-Urethral Sling Cannot Be a Permanent Solution? A Physics-Based Critique of the Hammock Theory and the Case for Physiological Continence Reconstruction

Ji-Hong Shen[1], Hongcheng Li[1], Dao-Ming Tian[1], Ling Li[1], Jiangna Gu[1], Xing-Qi Wang[1], Yuan Li[1], Qian Luo[1]

1. First Affiliated Hospital of Kunming Medical University, Kunming, China

For nearly three decades, the mid-urethral sling (MUS) has been the global standard for surgical treatment of female stress urinary incontinence. Yet its reign is unravelling. Regulatory bans and restrictions in multiple countries, mounting long-term complication data, and a deepening theoretical crisis have converged on a single, unresolved question: What is the physical nature of urinary continence? Is it a state of passive compression, as the hammock and integral theories assume, or is it a dynamic, reversible mechanical cycle governed by the laws of classical physics? The elastic collision perspective has been raised fragmentarily in prior critiques of the prevailing theories, and has entered formal academic debate, but a complete first-principles derivation and its surgical implications have not been systematically developed. Here we provide that derivation. We show that physiological continence is an elastic collision process, and we derive this conclusion from the principle of least action, Pascal's Law, the Poisson effect, and Laplace's Law. We demonstrate that the MUS, by introducing a permanent, non-contractile implant into an elastic system, transforms this elastic collision into an inelastic one. The long-term complications of MUS are therefore not technical failures—they are physical inevitabilities. We propose that the coefficient of restitution e should become the fundamental criterion for evaluating any surgical intervention for stress urinary incontinence. The era of designing pelvic floor surgery by anatomical intuition is ending. The era of designing it by physical necessity has begun.

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Correspondence: papers@team.qeios.com — Qeios will forward to the authors

1. The Unravelling of a Gold Standard

In 1996, Ulmsten and colleagues reported a novel ambulatory procedure for female stress urinary incontinence: a polypropylene sling placed at the mid-urethra under local anesthesia[1]. The mid-urethral sling (MUS) rapidly displaced Burch colposuspension and other traditional procedures to become the undisputed "gold standard." Its appeal was undeniable—minimally invasive, technically straightforward, with short-term cure rates exceeding 85%.

In 2018, Ireland became the first country to ban MUS. Scotland, France, the United Kingdom, Australia, and New Zealand have since imposed stringent restrictions[2][3][4]. The United States FDA, while stopping short of a ban, has issued multiple safety communications and reclassified transvaginal mesh products[5]. Simultaneously, MUS continues to be performed hundreds of thousands of times each year in China, the United States, and elsewhere—still under the label of "gold standard."

This global divergence is not merely a disagreement about complication rates. It is the symptom of a deeper, unresolved question that the field has avoided for thirty years: What is the physical nature of urinary continence? Is it a state of passive compression—as the hammock theory[6] and the integral theory[7] both assume—or is it a dynamic, reversible mechanical cycle governed by the laws of classical physics?

This question has not gone entirely unasked. Bergström, in a series of papers published between 2017 and 2018, argued that intra-abdominal pressure is not a static load but an impact force, and that continence involves elastic collision dynamics between the bladder and urethra—a direct challenge to the static ligamentous suspension model of the integral theory and the passive pressure-transmission model of the hammock hypothesis[8][9]. Petros, the originator of the integral theory, formally responded to this elastic collision critique in 2022[10], acknowledging its entry into the academic debate. A systematic framework articulating the physical principles of pelvic floor function has been proposed by Shen and colleagues, who introduced the self-locking and reciprocal-locking mechanism as a unified biomechanical theory grounded in the principle of least action and elastic collision dynamics (Shen et al., cited in [10]).

However, these prior contributions remain incomplete. Bergström's critique identified specific physical inconsistencies without providing a complete alternative mechanism or its anatomical expression. The

self-locking framework, while theoretically comprehensive, has not yet been presented with its full validation in an integrated format accessible to the broader scientific community.

The present work advances this debate decisively. We provide the complete physics derivation and the anatomical mechanism that together constitute a unified theory of pelvic floor function. We then propose a new evaluative criterion—the coefficient of restitution e—that can guide the design and assessment of continence surgery.

The answer to this question determines everything: which surgical designs are physically compatible with long-term pelvic floor health, and which are destined to fail regardless of how skillfully they are performed.

2. The Physics of Continence

2.1. Continence as an Elastic Collision

In classical mechanics, a collision is elastic if two conditions are met: total kinetic energy is conserved, and all deformation is fully recovered. The coefficient of restitution e equals 1. Human physiology offers several examples: the cardiac cycle, the respiratory cycle, and—we argue—the continence cycle.

Consider a healthy woman during a single cough. Intra-abdominal pressure surges from approximately 10 cmH_2O at rest to 100-150 cmH_2O within milliseconds. This is not a static load that builds gradually—it is an impact force, a collision-like event[8]. According to Pascal's Law, this pressure increment is transmitted uniformly to all pelvic organs—bladder, uterus, and rectum—simultaneously. There is no preferential downward force on the urethra. The premise of both the hammock theory and the integral theory—that abdominal pressure "compresses the urethra against a supportive layer" or that it is balanced by ligamentous tension—is physically untenable.

What actually occurs is more elegant. The levator plate and perineal body actively contract, tethering the bladder neck against the posterior surface of the pubic symphysis. This is not compression—it is elastic tethering. The bladder neck is closed (urethral radius $r \to 0$), and functional urethral length L is maintained at its physiological maximum. According to Poiseuille's equation—

$$Q \propto r^4/L$$

—where Q is leakage flow, when $r \to 0$, $Q \to 0$ regardless of intra-abdominal pressure. This is the r^0 effect: a zero-radius closure point guarded by adequate length.

When the cough subsides and the neural signal for active contraction is released, the elastic restoring force returns the bladder neck to its resting, open position. No additional "opening" force is required. The entire cycle—closure, pressure surge, pressure release, opening—is fully reversible, energy-conservative, and damage-free. The deformation produced by the cough is completely recovered. No residual strain accumulates.

This is the physical definition of physiological continence: an elastic collision with $e \rightarrow 1$.

2.2. The Principle of Least Action and the Evolutionary Imperative

Why did natural selection converge on elastic collision as the mechanism for continence? The answer lies in one of the most fundamental laws of physics: the principle of least action.

The principle states that a system evolving from state A to state B follows the path that minimizes the action $S = \int L \, dt$. For the pelvic floor, state A is urethral closure during storage, state B is urethral opening during voiding, and the cycle must be executed tens of thousands of times over a lifetime.

Natural selection faced an optimization problem: maximize continence reliability while minimizing the energy cost per cycle. Elastic collision is the only solution that satisfies both constraints. In an elastic collision, kinetic energy is fully conserved—the work done by muscle contraction during closure is stored as elastic potential energy, and this stored energy passively drives opening during voiding. The net energy cost of a complete closure-opening cycle approaches zero.

An inelastic alternative—in which the urethra is actively compressed and must be actively "pulled open" for voiding—would require additional energy input for every cycle. Over a lifetime of micturition, this energy cost would be prohibitive. Natural selection, operating under the principle of least action, could not converge on such a solution.

The anatomical features of the female pelvic floor—the active contraction and elastic recoil of the levator plate, the elastic tethering rather than rigid fixation of the bladder neck, the dynamic rather than static kinking of the mid-urethra—are all expressions of this evolutionary optimal solution. Elastic collision is not one possible way to achieve continence. It is the way that physics and evolution together have dictated.

2.3. Why Static Support Theories Violate Physical Law

The hammock theory posits that intra-abdominal pressure compresses the urethra against a supportive layer of endopelvic fascia and anterior vaginal wall, producing continence by passive occlusion[6]. The integral theory posits that continence results from the balanced action of ligaments suspending the urethra and muscles pulling against them[7]. Both theories share a fundamental assumption: that pelvic floor structures function as a static or quasi-static support system.

This assumption violates multiple physical principles simultaneously.

First, Pascal's Law dictates that pressure in a closed fluid system is transmitted uniformly in all directions. The abdomen, filled with incompressible fluid and semi-solid organs, is such a system. A cough produces a pressure increment that acts equally on the bladder dome, the uterine fundus, and the rectal wall. There is no vector of force that preferentially "pushes the urethra downward" onto a hammock.

Second, an elastic structure already in closure requires a "pulling-open" force to open—not further compression. If the urethra were truly "compressed closed" by abdominal pressure, then voiding—which typically involves a Valsalva maneuver and higher abdominal pressure—would be impossible. The urethra would be compressed more tightly, not opened. The fact that women can void effortlessly, often with elevated abdominal pressure, is direct empirical evidence against passive compression.

Third, the loading regime is dynamic, not static. Intra-abdominal pressure during a cough rises from baseline to peak in approximately 50-100 milliseconds. This is an impact load, not a gradually applied static force[8]. The biomechanical response of soft tissues to impact loading is fundamentally different from their response to static loading: inertial effects, wave propagation, and viscoelastic energy dissipation dominate the transient response. Static ligamentous suspension models cannot capture these dynamics.

Fourth, the structural capacity of the supposed "supporting" elements is orders of magnitude insufficient. The uterosacral ligament—the primary suspensory structure in the integral theory—has an ultimate tensile strength of approximately 5.38 N and a stiffness of 0.12 N/mm. By comparison, the anterior cruciate ligament of the knee has an ultimate tensile strength of 2,195 N and a stiffness of 306 N/mm. The levator plate generates a maximum active contraction pressure of only 36-46 cmH_2O, while cough-induced intra-abdominal pressure reaches 100-150 cmH_2O. The structures assigned to "support"

the pelvic floor are physically incapable of resisting the loads they are purported to bear. They must function by a different mechanism entirely.

3. The Mid-Urethral Sling as an Inelastic Element

3.1. What the MUS Introduces into the Elastic System

A mid-urethral sling is a strip of non-absorbable polypropylene mesh, permanently implanted beneath the mid-urethra. It exerts a constant, unregulated compressive force on the urethral lumen. In physical terms, the sling is an inelastic element inserted into an elastic collision system.

This single fact—that a permanent, non-contractile foreign body has been introduced into a system whose function depends on full elastic recovery—has consequences that are not probabilistic. They are deterministic.

3.2. Three Irreconcilable Physical Contradictions

Contradiction 1: Elastic collision degenerates into inelastic collision.

With each cough, sneeze, or physical exertion, the urethral tissue compressed beneath the sling undergoes deformation. Unlike the physiological mechanism—where deformation is fully recovered by elastic recoil—the constant compressive force of the sling prevents complete recovery. Each pressure spike leaves a residual strain in the periurethral tissue. The coefficient of restitution e progressively declines from approximately 1 toward values less than 1.

This is not a clinical observation requiring statistical validation. It is a material property. Any viscoelastic tissue subjected to constant compression and cyclic impact loading will undergo creep. In engineering terms, this is material fatigue. In clinical terms, it is the gradual decline in long-term continence efficacy and the emergence of new symptoms—frequency, urgency, incomplete emptying—that are typically attributed to "aging" or "patient factors" rather than to the inelastic element itself.

Contradiction 2: A constant compressive force cannot satisfy a variable physiological demand.

Intra-abdominal pressure is a continuous variable. It ranges from approximately 10 cmH_2O at rest, to 100-150 cmH_2O during a vigorous cough, to the coordinated detrusor contraction and Valsalva pressures of voiding. The sling provides a single, constant level of compression.

The surgeon adjusts sling tension intraoperatively, attempting to locate a "sweet spot" that balances continence during stress and free voiding at rest. This sweet spot is narrow. For many patients, it is physically impossible to achieve with precision. A sling that is slightly too loose: stress continence fails, and SUI recurs. A sling that is slightly too tight: voiding requires elevated detrusor pressure, the detrusor hypertrophies to meet this new workload, and detrusor overactivity (DO) develops over years of high-pressure voiding. The patient's presenting complaint shifts from "I leak when I cough" to "I cannot hold my urine long enough to reach the toilet"—her SUI has been replaced by OAB.

This is not a surgical complication in the conventional sense. It is the inevitable physiological response of a muscular organ forced to work against a constant, unphysiological resistance. The sling does not adapt to the patient. The patient's bladder must adapt to the sling—and that adaptation, over time, is pathological.

Contradiction 3: The urethra is transformed from a dynamic structure into a passive conduit.

The normal female urethra is mobile, elastic, and dynamically responsive to changes in posture and abdominal pressure. Its mobility is not a defect to be corrected—it is a functional requirement for the elastic collision cycle. The sling fixes the mid-urethra at a single position, restricting this physiological mobility.

In retropubic (TVT) procedures, the more anterior sling position produces greater urethral angulation during squatting—explaining the higher rate of obstructive voiding symptoms. In transobturator (TOT/TVT-O) procedures, the more posterior position reduces angulation—explaining the lower continence rate[11]. Neither position restores the native dynamic elasticity of the urethra. Both replace a dynamic adaptive structure with a static, passive one.

3.3. Complications Are Not Probabilities—They Are Physical Consequences

The classic complications of MUS—voiding dysfunction, de novo urgency and OAB, chronic pelvic and groin pain, and mesh erosion or exposure—are typically discussed as surgical "risks" that can be minimized by refined technique, improved mesh materials, or better patient selection.

This framing misrepresents their nature. If the introduction of an inelastic element into an elastic collision system inevitably degrades the system's elastic recovery, then the resulting clinical phenomena are not probabilities to be minimized. They are deterministic consequences of a physical incompatibility. Improved technique may shift the timing or severity of each individual manifestation, but it cannot

eliminate the underlying contradiction between a permanent static implant and a system whose function depends on full elastic recovery.

The global regulatory divergence—bans in some countries, continued unrestricted use in others—reflects a scientific vacuum. In the absence of a physics-based understanding of continence, regulators and clinicians have relied solely on clinical outcome data. But clinical data can be contested: differences in follow-up duration, outcome definitions, surgical technique, and patient selection produce conflicting conclusions. This is why, after three decades and thousands of publications, the MUS debate remains unresolved.

The physics of elastic collision provides what clinical data alone cannot: a mechanistic explanation for why the long-term failure of passive compression is inevitable, and a clear criterion—the coefficient of restitution e—for distinguishing physiologically compatible interventions from those that are physically incompatible.

4. The Self-Locking and Reciprocal-Locking Mechanism

4.1. A-Lock: The Primary Valve

If continence is an elastic collision process, how is it achieved anatomically? The self-locking and reciprocal-locking theory (Shen et al., cited in [10]) identifies two synergistic locks that share a common actuator: the levator plate–perineal body complex.

The A-lock (bladder neck tethering) is the primary valve. The levator plate and perineal body actively contract during any increase in intra-abdominal pressure, tethering the bladder neck against the posterior surface of the pubic symphysis. This produces the _r_⁰ effect—the bladder neck is closed, and Q → 0 regardless of pressure. Simultaneously, functional urethral length L is maintained at its physiological maximum.

The A-lock operates through what we term the "tethering effect": the levator plate contraction constrains the bladder base, locking its functional composite Poisson ratio at near zero. This directs pressure-induced deformation toward the posterior-superior bladder wall—a region without rigid constraint—where it is absorbed as elastic strain energy. The bladder neck is thereby shielded from the impact stress. This is the mechanism that makes elastic collision possible.

4.2. B-Lock: The Redundant Safeguard

The B-lock (mid-urethral kinking) is the secondary safeguard. The pubovisceral muscle and external urethral sphincter contract synchronously with the levator plate, producing a dynamic kink at the mid-urethra that further reduces the effective urethral radius r.

The B-lock provides redundancy: if the A-lock is momentarily compromised by extreme fatigue or an exceptionally violent pressure surge, the B-lock maintains continence. Critically, the B-lock is dynamic—its contraction force scales with intra-abdominal pressure, providing precisely the degree of additional closure required for a given stress. This stands in fundamental contrast to the constant, unregulated compression of the MUS.

4.3. The Failure Cascade

Postpartum injury to the levator plate or perineal body is a systemic injury to this shared actuator. The A-lock fails first: the bladder neck descends and opens under pressure, L shortens, and the r^0 effect is lost. The B-lock, still partially functional, cannot fully compensate—a mid-urethral kink cannot substitute for a closed bladder neck.

This is why most women with SUI exhibit both bladder neck hypermobility and reduced mid-urethral closing pressure. The two locks fail together because they share the same actuator.

4.4. What the MUS Actually Does—and Does Not Do

From the perspective of the self-locking mechanism, the action of the MUS is precisely defined. It places a passive, constant, non-dynamic obstruction at the mid-urethra. It partially simulates the B-lock—narrowing urethral radius r—but this "B-lock" is counterfeit: it has no dynamic regulation, no elastic recoil, and no coordination with the A-lock.

Critically, the MUS does nothing to restore the A-lock. If the A-lock has failed—if the bladder neck opens under pressure and L is shortened—placing a sling at the mid-urethra is equivalent to installing a secondary barrier downstream of a primary valve that no longer closes. Continence may be temporarily achieved by increasing outflow resistance, but the upstream pathology—bladder neck opening, stress concentration at the bladder base, loss of the tethering effect—persists uncorrected. Over time, this uncorrected pathology drives progressive deterioration: bladder base descent, worsening anterior

compartment prolapse, and the development of detrusor overactivity as the bladder works against a chronic outlet obstruction.

5. Physiological Reconstruction

5.1. Principles

If the preceding analysis is correct—if continence is an elastic collision, and MUS is an inelastic element that degrades this collision—then the design criteria for any surgical intervention for SUI follow logically.

- **First:** no permanent implants. Any non-contractile, non-degradable foreign body introduced into the pelvic floor will, over time, reduce the system's coefficient of restitution e below 1. This is not a hypothesis; it is a material consequence of viscoelastic tissue mechanics under constant compression and cyclic impact loading. Reconstructive surgery should use autologous tissue or absorbable materials that preserve the system's capacity for full elastic recovery.
- **Second:** restore the A-lock. The primary valve is the bladder neck tethering mechanism. Reconstruction of the levator plate and perineal body—restoring the active contractile capacity that tethers the bladder neck closed—is the cornerstone of physiological continence surgery. This restores both the _r_⁰ effect and functional urethral length L.
- **Third:** preserve elastic recoil. The reconstructed pelvic floor must remain capable of the elastic collision cycle: active contraction during stress, passive elastic opening during voiding. Any surgical fixation that rigidly immobilizes the bladder neck or urethra—even if it achieves short-term continence—has introduced an inelastic constraint that will, over time, degrade the system.

5.2. A New Criterion for Evaluating Continence Surgery

We propose that the coefficient of restitution e should become the fundamental criterion for evaluating any surgical intervention for stress urinary incontinence. A procedure that preserves or restores $e \to 1$ is physiologically compatible with long-term pelvic floor health. A procedure that permanently reduces $e < 1$ is physically incompatible—regardless of its short-term continence rate.

This standard does not demand the immediate abolition of MUS. It does, however, demand honesty about what MUS is: a non-physiological, inelastic intervention that trades short-term continence for long-term physical degradation of the system. It may have a role in carefully selected patients—the elderly, those with limited life expectancy, those who decline more extensive reconstruction—but it should not be

offered as a first-line, default solution to younger, physically active women whose elastic continence system remains partially intact and potentially restorable.

6. Conclusion

For thirty years, the mid-urethral sling has been the defining technology of female stress urinary incontinence surgery. Its rise was propelled by the elegance of its simplicity; its decline, where it has declined, has been driven by the accumulation of complications that no technical refinement could eliminate.

The physics of elastic collision explains both. The simplicity of MUS—placing a permanent compressive element at the mid-urethra—is also its fundamental flaw. It solves one problem (stress leakage) by introducing a permanent inelastic constraint into a system whose function depends on full elastic recovery. The complications that follow are not failures of surgical technique. They are the system's inevitable response to a physical incompatibility.

The elastic collision perspective has been raised before—by Bergström in his critique of the integral and hammock theories[8][9], and by Petros in his formal response[10]. What has been missing, until now, is the complete physics derivation and the anatomical mechanism that together move this debate from the exchange of opinion to the establishment of physical necessity.

The era of designing pelvic floor surgery by anatomical intuition is ending. The era of designing it by physical necessity has begun. The coefficient of restitution e—a parameter that can be independently measured, that makes clear predictions about long-term outcomes, and that distinguishes physiologically compatible interventions from incompatible ones—provides the criterion that the field has been missing. The mid-urethral sling, as the most widely used product of the intuitive era, deserves our respect for what it taught us—and our clear-eyed recognition of its physical limits. The patients we serve deserve the same.

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Declarations

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