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Editorial

Toward a Digital Twin of the Female Pelvic Floor

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Pelvic floor disorders (PFDs)-including urinary incontinence, pelvic organ prolapse, chronic pelvic pain, and sequelae of obstetric trauma - remain among the most prevalent and functionally debilitating conditions in women's health. Despite continuous advances in imaging, biomechanics, and urogynecologic surgery, clinical decision-making is too often constrained by fragmented data streams and cross-sectional "snapshots" of a dynamic, load-bearing, multi-tissue system. The emerging concept of the digital twin (DT) offers a tractable way forward: a continuously updated, computational representation of a system, informed by multimodal measurements and capable of simulating trajectories under alternative management strategies. In healthcare, digital twins have shown significant promise in managing chronic conditions, optimizing rehabilitation, and personalizing treatment [1-3]. A recent article lays out the foundational architecture for such a system in gynecology and urogynecology, motivating a shift from population-averaged heuristics to individualized, mechanistic care [4].

Why a digital twin - and why now?

Clinicians already triangulate between anatomy (ultrasound/MRI), function (urodynamics), and tissue properties (biomechanics). Yet these data typically live in silos, are interpreted qualitatively, and are not integrated into prospective predictions. A pelvic-floor DT would unify:

- Geometry (3D anatomy of muscles, fascia, ligaments, viscera and their spatial relations);
- Material properties (viscoelastic behavior of soft tissues mapped *in vivo*);
- Boundary/loading conditions (intra-abdominal pressure, cough/Valsalva, daily activities);
- Neural/motor control surrogates (muscle activation patterns inferred from functional testing);
- Symptoms and quality-of-life signals (patient-reported outcomes, wearable streams).

At its core, this is a bidirectional pipeline: new observations update the twin; the twin returns quantified risk assessments and counterfactual predictions that guide care. In women's health -where parity, aging, hormonal milieu, and prior interventions reshape failure modes over time -this longitudinal coupling is essential.

What would a pelvic-floor digital twin do?

1. **Phenotype with rigor:** Fusing imaging, biomechanical mapping [5], and functional testing can disambiguate superficially similar presentations (e.g. stress incontinence with fascial laxity vs. sphincteric deficiency). Quantitative decomposition of impairment improves target selection for physical therapy, bulking, slings, or prolapse repair.
2. **Forecast trajectories:** Recurrent training of predictive models on an individual's data enables estimation of near-term progression (e.g. prolapse stage drift) and long-term risks (e.g., symptom recurrence after repair), with credible intervals that reflect measurement noise and model uncertainty.
3. **Simulate interventions:** "Virtual trials" on the twin can approximate the mechanical and functional consequences of pelvic floor physiotherapy protocols, surgical configurations, or pharmacologic options before they are attempted *in vivo* - supporting shared decision-making and expectation management.
4. **Clarify complex pain and gynecologic pathology:** Integrating symptom maps with imaging and elastography may help localize contributors to pelvic pain and differentiate among conditions such as endometriosis, adenomyosis, and fibroids - especially when lesions are subtle or multifocal.
5. **Address obstetric injury and preterm birth risk:** A twin updated peri- and postpartum can identify tissue compromise (e.g. levator ani avulsion, perineal body disruption) and quantify recovery, guiding rehabilitation. Antepartum, a DT may help stratify spontaneous preterm birth risk by integrating cervical and myometrial metrics with clinical history [4].

A practical roadmap for *EC Gynaecology* readers

1) **Start from what clinics already measure:** Select a minimal, feasible data schema around which to build the twin: a standardized pelvic ultrasound protocol (2D/3D as available), a short biomechanical assessment (e.g. pressure/strain mapping or validated surrogates), a compact urodynamic panel where relevant, and harmonized symptom instruments. The point is not maximal technology at baseline, but repeatable signals with known error characteristics.
2) **Normalize and register:** Use an anatomical reference frame (patient-specific, not atlas-only) so that serial exams and modalities are co-registered. Even simple surface/landmark registration improves interpretability of before/after comparisons.
3) **Use actionable indices:** Use a small, interpretable set of composite parameters (e.g. a biomechanical integrity score, compartment-specific support scores, urethral closure reserve) that clinicians and patients can track over time. Keep feature definitions transparent and clinically grounded.
4) **Close the loop with prediction:** Begin with modest models: time-series regressors for symptom trajectories; logistic risk models for treatment response; finite-element approximations where tissue-level mechanics are critical. Validate internally with repeated measures from the same patient before expanding to federated cohorts.
5) **Embed in shared decision-making:** Present outputs as counterfactuals ("If we intensify pelvic floor therapy by X, the model projects Y% improvement in leakage episodes at 12 weeks") with uncertainty bounds and assumptions stated plainly. Visual, patient-friendly dashboards elevate adherence and satisfaction.

Validation, governance, and equity

A pelvic-floor DT must be prospectively validated against clinically meaningful endpoints: symptom reduction, objective function gains, complication rates, and durability. Methods should include:

- Test–retest reliability for core inputs (e.g., elastography repeatability; inter-rater agreement for imaging landmarks);
- Calibration and discrimination for predictive components (calibration plots, AUROC/PR where appropriate);
- Decision-curve analysis to confirm added clinical net benefit over standard practice.

Governance must address privacy, transparency, and bias. Given the sensitivity of pelvic health data, strict adherence to HIPAA/GDPR frameworks is non-negotiable; data minimization and on-device/federated learning approaches can reduce exposure. Models should be explainable at the level of feature attributions and mechanistic plausibility, with routine fairness audits across age, parity, and racial/ethnic groups - recognizing well-documented disparities in PFD burden and care pathways.

Finally, an equitable DT ecosystem requires cost-aware design: modular hardware, software that tolerates heterogeneous inputs (so centers without MRI or advanced elastography still benefit), and reimbursement strategies tied to demonstrable outcome improvement and reduced downstream costs.

What will change in practice?

- **From binary labels to graded capacity:** Instead of "meets criteria/does not," clinicians will counsel using **reserve** (how much function/support remains under load) and responsiveness (likelihood of improvement under a chosen modality).
- **From procedure-centric to mechanism-centric decisions:** Surgical and non-surgical options will be selected based on a quantified mismatch between load and support, not solely on anatomic stage or symptom severity.
- **From one-off visits to longitudinal stewardship:** The twin enables interval monitoring and early course-corrections, particularly in the critical postpartum and perimenopausal windows.

A call to action

For *EC Gynaecology's* readership - clinicians, physiotherapists, imaging specialists, and translational researchers - the digital twin is not a distant aspiration. The constituent technologies are clinic-ready; what is needed is integration with discipline. Early adopters can begin by standardizing data capture, building small but durable registries, and piloting decision support that is auditable and humble about uncertainty. Multicenter consortia should align on core outcomes and data elements to accelerate external validation and regulatory acceptance. Patients should be partners from the outset - co-designing interfaces and prioritizing what "success" means to them.

The central promise is straightforward: individualized, biomechanically truthful care that anticipates trajectories rather than reacting to failures. If we seize this opportunity with rigor and empathy, the digital twin can move from concept to clinical standard - and women living with pelvic floor disorders will feel the difference.

Conflicts of Interest

The author is a shareholder of Advanced Tactile Imaging, Inc. and is an inventor on relevant intellectual property.

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