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Female Pelvic Floor Biomechanics: Bridging the Gap

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Abstract

Purpose of review—The pelvic floor is a complex assembly of connective tissues and striated muscle that simultaneously counteract gravitational forces, inertial forces, and intraabdominal pressures while maintaining the position of the pelvic organs. In 30% of women, injury or failure of the pelvic floor results in pelvic organ prolapse (POP). Surgical treatments have high recurrence rates, due, in part, to a limited understanding of physiologic loading conditions. It is critical to apply biomechanics to help elucidate how altered loading conditions of the pelvis contribute to the development of pelvic organ prolapse and to define surgeries to restore normal support.

Recent findings—Evidence suggests the ewe is a potential animal model for studying vaginal properties and that uterosacral and cardinal ligaments experience significant creep, which may be affecting surgical outcomes. A new method of measuring ligament displacements *in vivo* was developed, and finite element models that simulate urethral support, pelvic floor dynamics, and the impact of episiotomies on the pelvic floor were studied.

Summary—This review highlights some contributions over the past year, including mechanical testing and the creation of models, which are used to understand pelvic floor changes with loading, and the impact of surgical procedures, to illustrate how biomechanics is being utilized.

Keywords

Pelvic floor biomechanics; ex-vivo mechanics; finite element analysis

Introduction

The pelvic floor consists of a complex and highly interdependent network of connective tissues and muscles designed to counteract gravitational forces, inertial forces and intra-abdominal pressures while providing support to the pelvic organs [1, 2]. When this network is compromised, pelvic floor disorders (PFDs) can occur including pelvic organ prolapse (POP).

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Approximately 30% of all women experience some degree of POP during their lifetime. Vaginal parity incurs the greatest risk; however, age, maternal birth injury, chronic straining, and obesity are also risk factors [3, 4]. Roughly 12.6% of women will seek surgical treatment for their symptoms, and of those who elect a native tissue repair, an estimated 40% will experience a reoccurrence within 2 years [5, 6]. While synthetic meshes have been widely adopted to improve surgical outcomes over native tissue repairs, meshes have also been associated with a higher than expected recurrence rates [7, 8]. As the pelvic floor comprises the primary load bearing structure of the pelvic organs, it has become increasingly clear that mechanics contributes to the onset of prolapse, and the failure of surgical interventions. With the ultimate goal of effectively preventing and treating POP, defining the loading conditions of the pelvis over the female lifespan is paramount [9].

In the last decade, progress has been made regarding the mechanical characterization of the vagina, bladder, urethra, rectum, cervix, uterus, connective tissues, and musculature of the pelvic floor [10]. However, some of the greatest remaining challenges stem from the ethical issues surrounding procurement of human tissues, in significant quantities, that span the average 35-year time gap between maternal birth injury and the onset of symptoms for POP [11, 12]. Thus, researchers have begun to implement cross-disciplinary techniques to help bridge the gap. Urogynecology is shifting towards computational methods, in which the results of mechanical, biochemical, and histological tests are used as inputs to complex mathematical models. The future of this field is in recognizing that a diverse set of factors contribute to the function and dysfunction of the pelvic floor, and that the application of biomechanics can help establish more specific research questions and identify paths that can lead to provable findings versus conjectures based on anecdotes.

This review highlights developments over the past year, ranging from ex-vivo mechanical testing, to complex finite element models, illustrating how the field has progressed at bridging knowledge between the known and unknown.

Experimental Mechanics

While no animal is a perfect model for humans, nonhuman primates, rodents, and swine, are frequently used to study pelvic floor biomechanics [13]. Their use depends on the research question of interest. Previous work established a basic mechanical understanding of the vagina, pelvic muscles, and supportive connective tissues using animal models, and this work is progressed with a few recent developments that will be reviewed.

Vaginal Properties

Parity is acknowledged as a leading risk factor in the development of POP, and the rodent and nonhuman primate are two animal models that are used to study the mechanical impact of parity. While rodents are relatively inexpensive and homogenous within breeds, they have small pup sizes, and are less likely to spontaneously incur birth injuries during delivery. This presents challenges in observing differences between nulliparous and parous groups with respect to maternal injuries that may manifest as a change in mechanics [12]. Alternatively, nonhuman primates are more likely to demonstrate differences in mechanical properties between the nulliparous and parous groups, similar to humans, but are expensive, and are a limited resource [12]. Thus, investigators study other animal models, with the hope of finding a model that incurs birth injury, and is less expensive to maintain. Knight et. al. investigated the uniaxial mechanical properties, collagen content, and collagen structure of the nulliparous and parous Dorset ewe, and found that the ewe could serve as a possible animal model alternative [12].

Similar to humans and nonhuman primates, parity incurs dramatic decreases in both the tangent modulus (a measure of material stiffness) and tensile strength of the vagina in the ewe. The vagina of the nulliparous ewe becomes more compliant with parity (i.e. decreased tangent modulus: 27.0 ± 11.5 MPa to 12.8+/−6.6 MPa ($p<0.025$). This suggests that understanding the mechanisms by which delivery negatively impacts vaginal mechanics may be ascertained through the ewe. Moreover, the parity status of nonhuman primates tends to be considerably higher than the ewe, raising questions for further investigation, such as determining the mechanical impact of single vs multiple births, with the hypothesis that an increase in parity will decrease mechanical properties [14].

Although mechanical outcomes are comparable between the nonhuman primate and the ewe, there are significant anatomical differences. The vagina is an intra-abdominal organ in the ewe (as opposed to retroperitoneal in humans and nonhuman primates), meaning that the in-vivo conditions are likely drastically different from nonhuman primates, and humans. While further investigation is necessary to determine if the ewe is a reliable animal model for pelvic floor biomechanics, the strength in this initial outcome is that the same mechanical testing protocols from the same laboratory were used for the animal models, allowing for a reliable cross-species comparison.

Uterosacral Ligament Complex

Of the connective tissues that provide support to the vagina, the uterosacral ligament complex (USL), which supports the upper vagina (apex) and cervix, has been most studied [10, 15, 16]. Restoration of apical support to the vagina is, indeed, key in achieving successful anatomical outcomes in the long term, and approximately 50% of what is observed as anterior prolapse is due to loss of support at the apex [17–19]. Additionally, addressing apical support at the time of hysterectomy for POP reduces recurrence and reoperation rates [20]. Characterizing the mechanical properties of the USL and its interdependency with other pelvic floor supportive structures will enhance our understanding of normal support, effective treatments, and surgical procedures.

Previously, the mechanical properties of the USL in primates, cadavers, and swine [21–25]. It was found that the tensile properties of the USL/Cardinal Ligaments (CL) are variable in all species, depending on the location with respect to the vagina, uterus, and cervix. In the ewe, the USL/CL complex was stiffer in the primary physiological loading direction (vagina to sacrum). It was also noted that the preferential orientation of fibers was congruent with this *in vivo* loading direction. This is similar to work by Tan et. al, who this past year determined the micro-structural and mechanical properties of the USL/CL complex in the swine [15]. The USL/CL specimens experienced large deformations, and experienced significant biaxial creep (continued increases in stretch when held at a constant force) in over a two-hour period. The largest differences, although not significant, were seen in the amount that the tissue deformed along the main loading direction of the USL/CL versus perpendicular to the main direction in response to small forces, with the latter direction demonstrating slightly more.

Overall, this study demonstrated that the connective tissues supporting the vagina display significant viscoelastic behaviors, indicating that the mechanical properties change based on how much time the tissue has experienced loading. Understanding these time-dependent mechanical properties are important in understanding the contribution of these tissues during events such as gestation, labor, and delivery; as well as identifying reconstruction materials that display similar behaviors [15].

An in-vivo imaging approach is an alternative experimental approach to improve our understanding of the USL/CL complex. Forces on the USL/CL complex can be approximated by observing the displacement of the uterus in dynamic stress magnetic resonance imaging (MRI) where it is allowed to displace physiologically. Recent work found that only 90g of traction force is required to match the uterine displacement visualized in MRI, suggesting that valsalva is not a significant physiological movement [26]. The finding also indicates that there may be additional factors to consider other than the USL/CL supports when trying to understand the positioning of the uterus. Furthermore, the tests that are performed clinically to define displacement of the pelvic organs and hence, surgical management employ forces that are at least 40 times greater than the force required, possibly leading clinicians to perform more aggressive procedures that are unwarranted. The magnitude of the forces experienced may not be as significant in contributing to failure as not providing any support to the appropriate locations. Studies such as this, demonstrate that MRI combined with mechanics can hold a wealth of information; and that this approach can be applied to improve our understanding the pelvic floor.

Experiments such as those described in this section provide insight into how these tissues behave from a mechanical standpoint and provide important first approximations that can serve as inputs into computational models to formulate new questions and refine our notions of what is plausible versus what is not.

Computational Mechanics: Finite Element Modeling

Finite element (FE) analysis is a method that determines approximate solutions to complex problems by breaking them into smaller interconnected pieces (elements) for which the mathematics is tractable. Strengths include the ability to approximate solutions to problems that cannot be tested physically due to budgetary, ethical, or practical constraints. However, major weaknesses are that solutions are only as good as the assumptions and inputs used to develop the model. Thus, answers that look reasonable and clinically plausible, could be incorrect and subject to unconscious biases. Findings must be validated and verified before establishing them as truth. In the field of pelvic floor mechanics, our understanding of the inputs (e.g. properties of tissues) and validity of the assumptions (e.g. how tissues interact) are rudimentary, at best. Thus, clinicians should interpret models with caution and question model assumptions. Nevertheless, the introduction of finite element modeling to Urogynecology has been monumental. Researchers are able to recreate and test a number of scenarios related to POP, such as vaginal birth, maternal muscle and connective tissue injury with vaginal birth, and the impact of repetitive strain [27]. Most models used to-date, however, are patient-specific (based on a single patient) so the interpretation of findings as they relate to broad populations of individuals should always be questioned [28].

One of the most anatomically complete pelvic models to date, contains 44 different structures, based on a 21-year-old healthy patient. This model was developed to determine the role of individual structures on urethral support [27]. Uniformly distributed pressures were applied to the model to simulate a maximal strain maneuver. As a first step toward validating the model, gross behaviors were compared with dynamic MRI images of a strain maneuver. It was found that the vaginal wall, puborectalis muscle and pubococcygeus muscle were pivotal in providing urethral support. When these factors were simulated as weakened, they produced large urethral excursion angles of 20.1, 19.4, and 18.8 degrees, respectively. Simulations weakening the levator muscles led to angles of more than 30 degrees. In contrast, weakening the illiococcygeus, piriformis, coccygeus, and obturator internus produced angles that were less than 17 degrees. Additionally, this study identified patterns of pelvic floor deformation, through changing combinations of weakened muscles, that could be further explored in future studies.

The same model was used to study the dynamics of the pelvic floor during athletic activities [29]. A jump landing was simulated based on experimental accelerometer data collected from individuals. First, the model demonstrated two distinct types of pelvic floor deformations that occur during a jump. The first deformation can be described as a “leaning forward compression”, where the bladder is pressed against the pubic bone and stretched in the antero-posterior direction. Following this movement, the bladder “bounces back”. The data demonstrates that this activity differs significantly from a maximal strain maneuver, suggesting that it may not be the best method to detect SUI clinically in female athletes. Instead, the model suggests that pelvic floor deformation, and not urethral hypermobility, is more important in predicting SUI.

In a separate study, finite element modeling was used to simulate varying degrees of bladder fullness, (from 0% to 100%) to determine effects on the anterior vaginal wall. Mechanical strain (a measure of how much the tissue deformed) was reported as four times as high at 100% bladder fill when compared to 10% bladder fill. Thus, a bladder fill of at least 60% is recommended to assess anterior vaginal prolapse. When vaginal stiffening increases, stress (force per unit area of tissue) was distributed more regionally throughout the anterior vaginal wall; however, the peak stress value (1.98 ± 0.05 MPa) changed minimally. These simulations suggest that measuring pressures in a clinical setting may not provide an adequate indication of deterioration of the anterior vaginal wall. This demonstrates that there may be a role for diagnostic and computational models to be used in conjunction with clinical measurements to improve clinical care [9].

Finite element modeling can also be applied to understand circumstances surrounding delivery, and birth injury, one of the primary risk factors for the eventual development of POP. The episiotomy, an incision into the perineal body to facilitate delivery, was previously one of the most common surgical procedures performed in the United States. However, the benefits versus maternal risks have come into question. Now, clinicians only perform episiotomies when complications necessitate an expedited delivery. As damage to pelvic floor muscles is a leading risk factor in the later development of PFDs, it is crucial that we understand how the episiotomy procedure impacts the pelvic floor during normal delivery [30]. To address this problem, a FE model of the medial lateral episiotomy was simulated during passage of a fetal head [31]. The investigators then quantified damage within the model for both normal and episiotomy assisted deliveries. They found that both conditions resulted in an increase in quantified damage in the pubovisceral muscle, however the episiotomy appeared to reduce the extent of the damage. While this study provides valuable information showing that an episiotomy can be protective to surrounding tissues, the degree to which it is protective still needs to be further investigated as this model becomes more refined. Overall, the damage caused by performing the episiotomy needs to be balanced with its potential to protect the pubovisceral muscle from damage in order to minimize future risk for POP.

It is well-known that the outcome of surgical procedures to repair POP are in part due to the unique parameters of each patient, in addition to surgical practices, including but not limited to the approach and type of materials used for repair. Jeanditgautier et. al. investigated how the size of a simulated mesh impacted mobility of pelvic organs in an abdominal sacrocolpopexy procedure [32]. Consistent with mechanical principles, it was found that larger meshes decreased the mobility of the pelvic organs. Indeed, increasing the amount of mesh in contact with the vagina increased support and decreased pelvic organ descent. Additionally, it was observed that the suture attachments to the vaginal apex were a site of high stress concentrations as the total force of the mesh was transferred to the vagina over the small area where the suture was placed. This stress can be more evenly distributed by placing more sutures, which is also consistent with basic mechanical principles. In this simulation, the number of sutures had little effect on the mobility of the pelvic organs, suggesting more is likely better. It should be noted, however, that this study does not factor in the biological response to suture or increased mesh burden. Thus, this study provides strong support for a research question to be tested experimentally.

Conclusion

While there are still many questions that need to be addressed, significant progress has been achieved over the past year with respect to pelvic floor biomechanics. Some of the challenges and hurdles associated with this field of research are being approached with innovative solutions that explore new animal models, apply mechanical tests that have been successful in other fields, and quantify medical diagnostic images in ways that lay the groundwork for clinically relevant care. Furthermore, the field is creating models that are helping to reveal mechanisms that contribute to a well-functioning pelvic floor leading to the eventual development of improved surgical treatments and prevention measures.

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Conflicts of Interest:

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***Special interest**

**** Outstanding interest**

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Key Points

- 1: Additional animal models should be considered, with care.
- 2: Despite the challenges, more robust mechanical tests (i.e. creep, biaxial tests) should be considered to help further elucidate the mechanical properties of the pelvic floor.
- 3: More accurate mechanical data and geometric models can be combined to create mathematical finite element models, that can further help predict and understand PFDs.