Review Article | Basic and Mechanism Sciences

Structural, functional, and dysfunctional pelvic anatomy

Bernard Liedl[1]^, Giuseppe Dodi[2]^, Hiromi Inoue[3]^, Menahem Neuman[4,5]^, Elisabeth del Amo[6]^

[1]Centre for Reconstructive Urogenital Surgery, Urology Clinic Munich, Planegg, Germany; [2]Department of Colorectal Surgery, University of Padova, Padova, Italy; [3]Urogynecology Center, Shonan Kamakura General Hospital, Kamakura, Japan; [4]Bar-llan University Israel, Ramat Gan, Israel; [5]Negev University, Beersheba, Israel; [6]Hospital del Mar, Barcelona, Spain

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Correspondence to: Bernard Liedl, MD. Centre for Reconstructive Urogenital Surgery, Urology Clinic Munich, Germeringer Str. 32, 82152 Planegg, Germany. Email: bernhard-liedl@t-online.de.

Abstract: The structural basis of the Integral Theory is holistic. Four main pelvic muscles interact holistically with five main pelvic ligaments to maintain pelvic organ structure and function. The vagina is structurally weak. The support it provides to the bladder base is contingent on being stretched by opposite pelvic muscle forces, much like a trampoline. Its main role is to transmit muscle forces to facilitate continence, evacuation and control of urgency. Therefore, as an organ that cannot regenerate, the vagina should be conserved, and not excised. The ligaments provide the main structural support for the organs and are the most vulnerable part of the anatomical system to injury because their structural collagen is depolymerized prior to labour, and stretched during labour. Further ligament weakening occurs after menopause due to collagen breakdown. Hence, collagen loss is the main cause of organ prolapse and lower urinary tract symptoms (LUTS). The strengthening of damaged ligaments, whether surgically or non-surgically, can improve or cure symptoms and prolapse. Because collagen loss in ligaments is a principal cause of dysfunction in older women, collagen-creating techniques are advised: precisely inserted tapes to create neoligaments, or wide-bore No. 2 or No. 3 polyester ligament sutures instead of dissolvable sutures.

Keywords: Pelvic organ prolapse; ligaments; pelvic floor muscles; collagen; lower urinary tract symptoms surgery (LUTS surgery)

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Introduction

The 4-minute video abstract (Video S1) summarizes the key anatomical points; viewing it *a priori* is recommended.

The aim of this contribution to the *ATM* Integral Theory Paradigm (ITP) issue is to describe the structural anatomy of the pelvic muscles and ligaments and the pathways leading to ligament damage sufficiently to lay down an anatomical foundation for the ITP papers which follow.

With reference to *Figure 1* (1), the structural basis of the Integral Theory (2) was the discovery that:

- Four main pelvic muscles, pubococcygeus, levator plate, conjoint longitudinal muscle of the anus, puborectalis and five main pelvic ligaments, pubourethral, cardinal, uterosacral, arcus tendinous fascia pelvis, and perineal body interact to maintain pelvic organ structure and function (*Figure 1*).
- Ligaments structurally support organs and are the

^ ORCID: Bernard Liedl, 0000-0002-8683-5468; Giuseppe Dodi, 0000-0002-8683-5468; Hiromi Inoue, 0000-0002-1614-467X; Menahem Neuman, 0000-0003-0934-4240; Elisabeth del Amo, 0000-0002-7351-7129.

most vulnerable to damage.

- ❖ The vagina is structurally weak; its main role is for function, and should be conserved, not excised.
- ❖ Weakening of collagen, the main structural component of ligaments, is the main cause of organ prolapse and lower urinary tract symptoms (LUTS).
- ❖ Strengthening damaged ligaments, whether surgically or non-surgically, can improve or cure symptoms.
- ❖ For postmenopausal women, collagen-creating techniques to strengthen ligaments are advised.

With reference to *Figure 1*, the functional basis of the Integral Theory (2) was the discovery that:

- ❖ Three oppositely acting reflex muscles, pubococcygeus (PCM), levator plate (LP), and conjoint longitudinal muscle of the anus (LMA) contract against the pubourethral (PUL) and uterosacral ligaments (USL) to control urethral closure, evacuation and to support bladder stretch receptors "N" from activating premature emptying ("urge incontinence") (*Figure 1*). Video S2 (ultrasound) shows the action of three reflex directional muscle forces, forwards, backwards, downwards. A fourth muscle, puborectalis, reflexly joins the other three to help enact anorectal closure and evacuation (3) (Video S3).

Highlight box

Key findings

- Control of the bladder and rectum is from outside the organ, from muscles and ligaments, with ligaments the most vulnerable to damage because of collagen loss by birthing and age.

What is known and what is new?

- Prevalence of vaginal excision for prolapse indicates belief that the vagina is the cause; the role of ligaments is ignored.
- The role of collagen in pelvic floor function and dysfunction is fundamental.
- Ligaments support organs with collagen, their main structural component.
- Collagen is vulnerable to damage from childbirth and deterioration by age.
- Defective ligament collagen causes both symptoms and prolapse.

What is the implication and what should change now?

- There is a distinct difference in collagen ligament content between premenopausal and postmenopausal women.
- Native ligament repairs work satisfactorily in premenopausal women.
- For older women, collagen creation methods such as slings provide a higher cure rate and should be considered.

The muscles

There are four main pelvic muscles (*Figures 1*,*2*). Three pelvic muscles, PCM, LP and conjoint LMA are entirely reflex (*Figure 1*, large arrows). The PCM attaches to the lateral part of the distal vagina and to the descending part of the PUL (4). Its medial part contracts forwards against the PUL (*Figures 1*,*2*). Its lateral part contracts backwards against the PUL, sweeps backwards to join its contralateral muscle to join with iliococcygeus to form the LP (*Figure 2*). LMA takes fibres from the LP, PCM, and inserts into the external anal sphincter (EAS) (*Figure 2*). The LMA contracts downwards against the USL (*Figure 1*). The puborectalis muscle (PRM) contracts directly against the pubic symphysis (PS) (*Figures 1*,*2*). It acts as both a voluntary muscle (squeezing upwards "Kegel") and as a reflex muscle to contract for anorectal closure and relax for defecation.

The ligaments

The ligaments (*Figure 1*) contain nerves, blood vessels and smooth muscle (2) and so they actively participate in all the functions of the pelvic muscles which pull against them. Collagen is the main structural component of ligaments (2). With reference to *Figure 1*, the PUL is a short ligament, about 4 cm long *in vivo*, and attaches to the mid urethra, also to the PCM and the distal vagina. USLs originate from S2–4, are attached loosely to the lateral walls of the rectum by fine ligamentous structures and insert into the posterior wall of the cervix. At a distance, 2 cm from the cervix, the USLs support the pelvic visceral plexus ganglions, sympathetic (T11–L2) and parasympathetic (S2–4). The arcus tendineus fascia pelvis (ATFP) suspends the vagina laterally, arising just above the PUL behind the symphysis and inserting into the ischial spine. *In vivo*, the USLs are about 9–10 cm long. With reference to *Figure 3*, the perineal body is suspended by the deep transversus perinei ligaments. These are about 4 cm long and insert behind the junction of the upper 2/3 and lower 1/3 of the descending ramus (5,6).

Simplistically, ligaments are the structural components of the pelvic floor, while the vagina is concerned with the function of transmitting the muscle forces which open and close the urethra (2). The collagen in ligaments is collagen 1, which is much stronger than the collagen 3, and

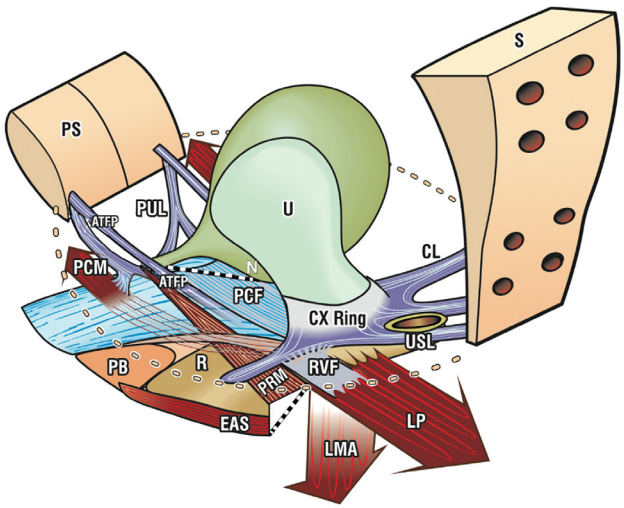

Figure 1 Structural and functional anatomy of the pelvic floor. Broken lines represent the "open" position of the bladder base/urethra and anorectum during evacuation. Reused from (1). Permission from Peter Petros, who retains ownership of the copyright. CX, cervix; N, urothelial stretch receptors; R, rectum; U, urethra. Bone: PS, pubic symphysis; S, sacrum. Suspensory ligaments: PUL, pubourethral ligament; ATFP, arcus tendineus fascia pelvis; USL, uterosacral ligament; CL, cardinal ligament. Muscles: PCM, pubococcygeus muscle; LP, levator plate; LMA, conjoint longitudinal muscle of the anus; PRM, puborectalis muscle. Supporting fascia: PCF, pubocervical fascia; RVF, rectovaginal fascia. Perineal anchoring structures: PB, perineal body; EAS, external anal sphincter.

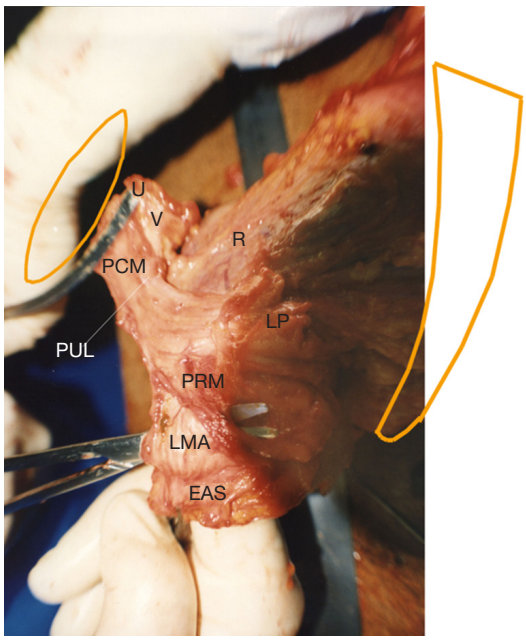

Figure 2 The muscles. Anatomical specimen from a female cadaver, cut away from its bony insertions. The bladder and vagina have been excised at the level of bladder neck. Reused from (1). With permission from Peter Petros; retains ownership of the copyright. U, urethra; V, vagina; R, rectum; PCM, pubococcygeus muscle sweeping behind R to merge with the contralateral side and ileococcygeus to form the LP; LP, levator plate; PRM, puborectalis muscle; PUL, insertion of pubourethral ligament into PCM; EAS, external anal sphincter; LMA, conjoint longitudinal muscle of the anus.

elastin which give the vagina its elasticity. The differential strengths of structure, ligaments with a breaking strain 300 mg/mm^2 and the vagina with 60 mg/mm^2, reflect the different roles of each (7).

The vagina

The vagina is the emptying tube for the uterus, fetus and menstrual blood. A tensioned vagina controls the afferent bladder evacuation signals from urothelial stretch receptors "N" being stretched by the PCM and the LP to support "N" from below (*Figure 1*). "N" are sensitive to the hydrostatic pressure of the urine. The vaginal tension below "N" is regulated by muscle spindles in the PCM and LP. The tension must be sufficient to stop the nerves from firing off afferent emptying impulses, but sufficiently elastic to allow separate closure of the distal urethra by PCM and the bladder neck by the LP/LMA.

The urethra and anus

Urethra and anus are composed of smooth muscle, collagen, and elastin. They are the emptying tubes for bladder and rectum. They are closed for continence and opened for evacuation by the external, cortically directed action of the four pelvic muscles (*Figure 1*). Anal stretch receptors are hypothesized to act similarly to those of the urothelium and are considered to be situated at a level just above the insertion of the LP into the posterior wall of the rectum (*Figure 1*).

Resources for further reading

See Petros and Ulmsten's studies (https://obgyn.onlinelibrary.wiley.com/toc/16000412/1990/69/S153) for bladder function and dysfunction (2).

See Petros and Swash's study (https://www.researchgate.

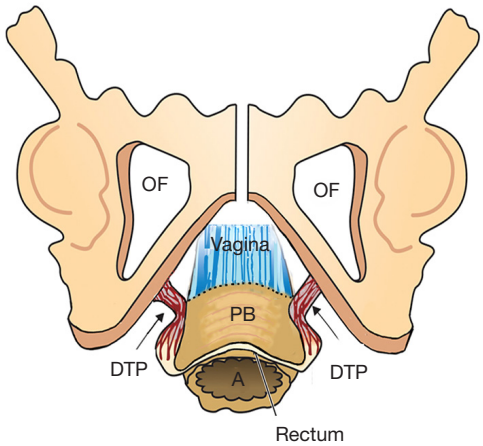

Figure 3 PB. The lower part of the vagina has been cut away. The PB is suspended from the pubic rami by the DTP ligaments. These are 4 cm long. They insert behind the descending rami, exactly between the upper 2/3 and lower 1/3. Reused from (1). With permission from Peter Petros; retains ownership of the copyright. OF, obturator fossa; PB, perineal body; DTP, deep transverse perineal; A, anus.

net/publication/267778578_The_MusculoElastic_Theory_of_anorectal_function_and_dysfunction) for anorectal function and dysfunction (3).

Role of muscles/ligaments in continence control

The bladder and bowel have only two modes, open or closed; these are cortically directed. The pelvic muscles externally close the bladder/bowel emptying tubes for continence, externally open them for evacuation (*Figure 1*, broken lines). The directional muscles stretch the organs bilaterally to prevent the bladder/bowel stretch receptors from prematurely activating micturition and defecation ("urge incontinence") (2,3).

Urethral closure on effort

With reference to *Figure 1*, forward contraction of the PCM stiffens the posterior wall of the distal vagina, distal urethra and the PUL; the LP stretches the proximal vagina and urethra backwards to stiffen them; the LMA pulls the now semi-rigid bladder base down against USLs to rotate it downwards to close the urethra at the bladder neck (like kinking a garden hose) (see forward closure of urethra, Video S2).

Anorectal closure on effort

With reference to *Figure 1*, forward contraction of the PRM stiffens the anterior wall of the rectum; forward contraction of the PRM stiffens the posterior wall of the rectum; the LP contracts backwards against the PUL to stretch the rectum backwards to render it semi-rigid; the LMA pulls against USLs to rotate the now semirigid rectum downwards around the contracted PRM to close the anorectal angle, kinking the rectum like a garden hose (see anorectal closure action of pelvic muscles, Video S3).

Micturition

Once the micturition reflex is activated, the patient feels an urge to go. The PCM relaxes, taking the forward pressure off the distal vagina and this allows the LP/LMA to stretch the vagina, trigone and bladder base backwards and downwards to open out the posterior wall of the urethra, exponentially lowering the resistance to urine flow, to enable emptying (2,8) (see micturition xray myogram, Video S4).

Defecation

The process for defecation is very similar to the micturition process, except that it is the PRM which relaxes. With reference to *Figure 1*, when the PRM relaxes, the LP/LMA pull open the posterior wall of the anorectum (broken lines). The PRM continues contracting to stiffen the anterior wall of the anorectum. External opening of the neorectum by pelvic muscles immediately prior to defecation lowers the intra-anal resistance to enable emptying (3,9) (see Video S5).

Anatomical pathogenesis of structural dysfunctions

According to the ITP, the key concept in pathogenesis of structural dysfunctions of the pelvic floor is ligament weakness caused by collagen deficiency. The main causes of collagen weakening are pregnancy and childbirth and collagen degeneration after the menopause. In a small group of women, congenital looseness of ligaments may also cause dysfunction.

Ligament overdistension may affect prolapse, symptoms, muscle/bone attachments

Though the ligament collagen has been softened by

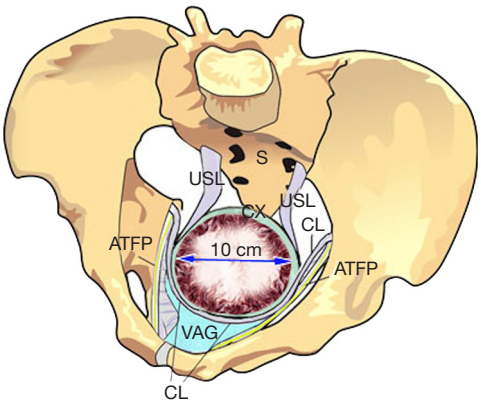

Figure 4 Upper end of the birth canal. Reused from (1). With permission from Peter Petros; retains ownership of the copyright. ATFP, arcus tendineus fascia pelvis; CL, cardinal ligament; CX, cervix; USL, uterosacral ligament; VAG, pubocervical fascia of vagina attached to CL and anterior cervix; S, sacrum.

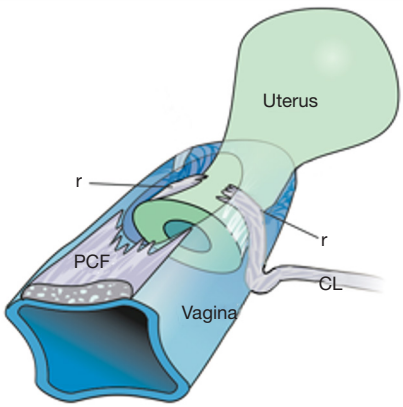

Figure 5 Transverse defect cystocele causation. Excessive pressure by the head may "r" the attachments of the CL and fascial layer of the vagina (PCF) to the CL and cervix. Note how the torn CL prolapses to the side of the cervix. The bladder overlying the vagina descends much like a trapdoor as a cystocele (transverse defect). Reused from (1). With permission from Peter Petros; retains ownership of the copyright. r, rupture; PCF, pubocervical fascia; CL, cardinal ligament.

relaxin and other hormones, a head at full dilatation (10 cm) places enormous pressure on the proximal 5 cm of the ligaments surrounding it. With reference to *Figure 4*, the cardinal ligaments (CLs), USL, and the attachments of the pubocervical fascia layer of the vagina may stretch or rupture at childbirth. The CL stretching or rupture may

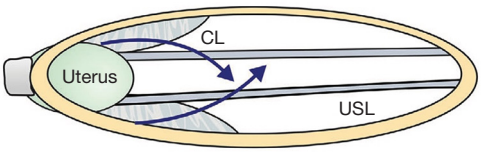

Figure 6 Causation of uterine prolapse. A 3rd or 4th degree uterine prolapse is caused by elongated USLs and usually, CLs also. Reused from (1). With permission from Peter Petros; retains ownership of the copyright. CL, cardinal ligament; USL, uterosacral ligament.

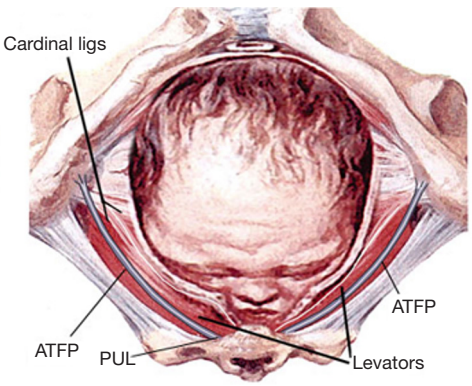

Figure 7 Structural damage at birth canal outlet. "levators" = collagenous insertions of the pubococcygeus muscle and puborectalis muscle to the symphysis. Reused from (1). With permission from Peter Petros; retains ownership of the copyright. ATFP, arcus tendineus fascia pelvis; PUL, pubourethral ligament.

cause transverse defect cystocele (*Figure 5*). USLs may elongate to cause uterine prolapse (*Figure 6*).

With reference to *Figure 7*, the expanding head even when fully flexed (9.4 cm) places enormous pressure on the PUL and the pelvic muscles at their insertion to the symphysis to cause stress urinary incontinence (SUI) and dislocated PCM/PRM insertions to the symphysis (10) (*Figure 8*).

With reference to *Figure 9*, the perineal body, and its suspensory ligaments (deep transversus perinei), are especially vulnerable to over-stretching or even rupture. With a deflexed head (11.2 cm diameter), the pressure of the emerging head is far greater, and damage may occur to the vagina, rectum, perineal body muscle and ligamentous attachments.

With reference to *Figure 10*, at "3" the head (circle) can overstretch uterosacral (USL) ligaments to cause uterine prolapse and enterocele. If the lateral ligamentous

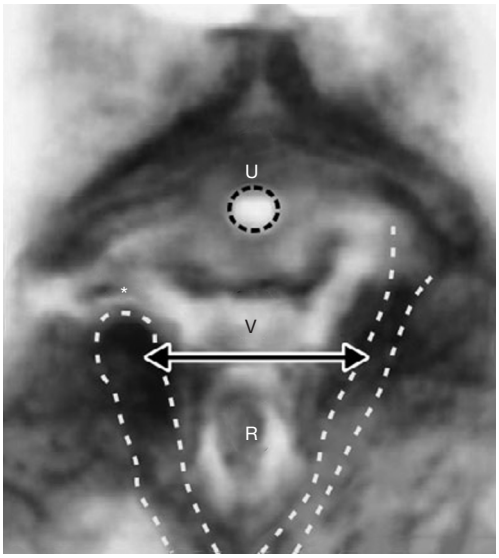

Figure 8 4D ultrasound of levator hiatus avulsion. View from above of the levator hiatus (arrows). Asterisk denotes a right-sided avulsion of pubococcygeus and/or puborectalis from its bony insertion point as a consequence of overdistension (see *Figure 7*). The pelvic muscles are outlined by broken lines. Reused from (1). With permission from Peter Petros; retains ownership of the copyright. U, urethra; V, vagina; R, rectum.

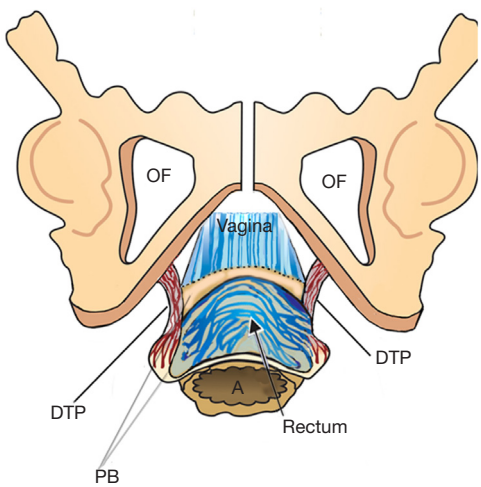

Figure 9 Pathogenesis of DPS. The PB has been stretched, narrowed, and flattened; the rectal serosa has been broken and rectal mucosa (labelled "rectum") has emerged through the broken serosa and spread laterally to adhere to the vagina and PB. The DTP ligaments are elongated and displaced to cause DPS. Reused from (1).With permission from Peter Petros; retains ownership of the copyright. DPS, descending perineal syndrome; OF, obturator fossa; A, anus; DTP, deep transversus perinei; PB, perineal body.

attachments of the USL to the rectum "R" pull the anterior rectal wall forwards as USLs lengthen, the anterior rectal wall may be stretched forwards to cause rectal intussusception (11) (*Figure 11*), which can be cured by USL repair (12); at circle "2", the CL elongation or rupture may cause cystocele'(transverse defect); at circle "4", perineal damage may cause rectocele and descending perineal syndrome; at circle "1", excess pressure on the levator muscles may dislocate or tear their collagenous insertions to symphysis pubis, while excess pressure on PUL may cause stress incontinence.

The damaged ligaments

The damaged ligaments fall into three natural zones (*Figure 10*). Anterior: external meatus to bladder neck; middle: bladder neck to cervix; posterior: cervix to introitus.

Damaged vaginal tissue

The vaginal "fascia" is the musculo-elastic layer of the vaginal wall. The anterior vaginal support of the urethra distally is called the "suburethral vaginal hammock"; more proximally, the vaginal support of bladder base is the "pubocervical fascia". The posterior vaginal wall (rectovaginal or Denonvillier's fascia) is attached proximally to the cervix and USLs, and is supported distally by the perineal body, which attaches it to the rectum.

The numbers in *Figure 10A*, causatively correlate with the same numbers in the diagnostic algorithm (*Figure 10B*), as regards prolapse, ligament damage and LUTS symptoms. For example, circle 3, damage to the USL may cause USL damage, uterine prolapse, and all the symptoms in the left zone.

Effects of age on native ligament repair

The dramatic effect of age and hormone withdrawal at menopause was demonstrated in a comparative study by Shkarupa *et al.* (13). Results at 18 months from native tissue plication of cardinal and USL gave 79.6% prolapse cure for premenopausal women but only 15.4% cure for postmenopausal women. The cure rates for urge and nocturia symptoms, were 87.7% and 67.3% against 17.9% and 15.4% respectively. The authors concluded that postmenopausal women required collagenopoietic slings for adequate repair of their prolapse and symptoms. This comment has been validated by many studies in older women using slings, some with large numbers (14-24), including high 5 years (14) and 10 years (15) cure rates for

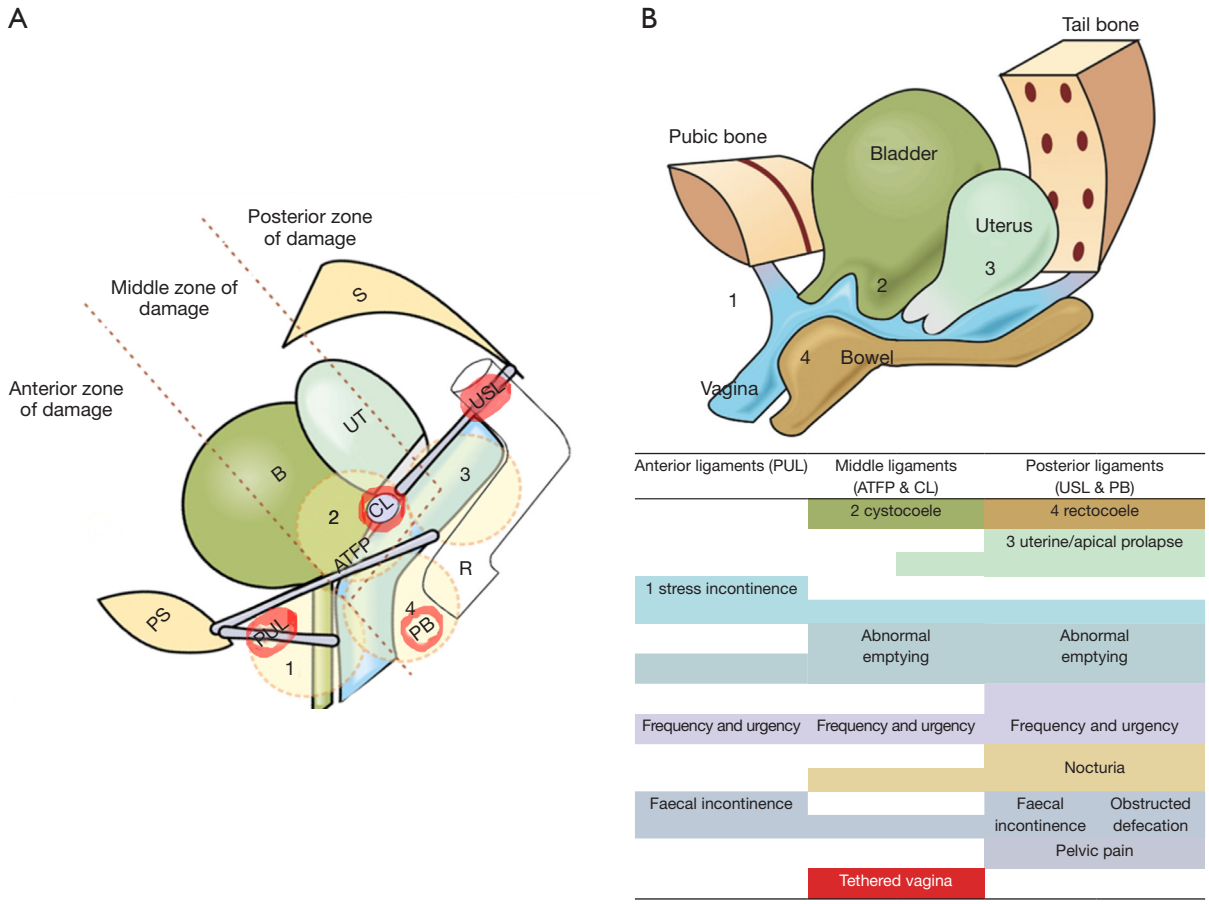

Figure 10 Anatomical pathway from damaged ligaments lead to a symptom-based diagnostic algorithm. (A) Head descending down the vaginal birth canal (blue). As the head descends down the vaginal birth canal, it damages the vagina and ligaments at 4 levels, shaded in red, (circles numbered 1–4). The circles and numbers 1–4, causatively correlate with specific prolapses and symptoms in the right figure, also numbered 1–4 in the three columns. The numbers 1–4 also correlate anatomically with the figure above the algorithm. (B) The diagnostic algorithm summarizes the causative relationship between anatomical damage of ligaments and vagina (circles 1–4, left figure), to prolapse and symptoms in three anatomical zones (numbers 1–4, right figure). The height of the bar indicates incidence of the symptom in that zone. Reused from (1). With permission from Peter Petros; retains ownership of the copyright. ATFP, arcus tendineus fascia pelvis; B, bladder; CL, cardinal ligament; PB, perineal body; PS, pubic symphysis; PUL, pubourethral ligament; S, sacrum; USL, uterosacral ligament; UT, urinary tract.

both pelvic organ prolapse (POP) and pelvic symptoms.

The anatomical basis of the ITP diagnostic system

The algorithm (*Figure 10B*), uses symptoms to diagnose damaged ligaments and infer the presence of prolapse, which is often minimal. Symptoms are ticked in each box where they occur, even if they occur only "sometimes". The conditions in all three columns may be caused by laxity of ligament(s) in that zone.

Diagnosis of ligament damage is by deduction

With reference to the Diagnostic Algorithm (*Figure 10B*), nocturia, chronic pelvic pain, obstructive defecation are uniquely caused by posterior zone ligament defects (USL). Stress urinary or stress fecal incontinence are uniquely caused by anterior zone (PUL) defects. These zones are ticked first and are the starting point for diagnosis of ligament damage and inferring of specific prolapses. The algorithm is based on individual symptoms occurring in an individual patient. Definitions such as, "mixed

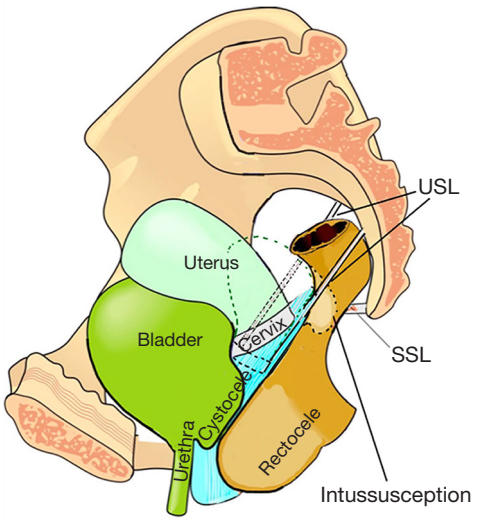

Figure 11 USL causation of rectal intussusception. Anterior rectal wall intussusception caused by elongation of the USLs attached to the lateral walls of the rectum. Reused from (1). With permission from Peter Petros; retains ownership of the copyright. SSL, sacrospinous ligament; USL, uterosacral ligament.

incontinence", "overactive bladder" (OAB), "Posterior Fornix Syndrome" (PFS), which combine often co-occurring symptoms have no place in this diagnostic algorithm. The individual symptoms from an individual patient with these conditions must be entered into the algorithm, so a diagnosis of ligament causation can be inferred. With reference to *Figure 10B*, SUI, when it co-occurs with urge is called "mixed incontinence". The SUI part is caused by a loose/weak PUL, but the urge may be caused by ligament defects in any of the three zones. OAB (urge, frequency) may be caused by any zone, but if there is also nocturia, the main ligament damage is likely the USL in the posterior zone. As regards PFS symptoms (co-occurrence of urge, frequency, nocturia, abnormal emptying, and chronic pelvic pain), the presence of nocturia and abnormal emptying place causation firmly with the USL (note: often the worst PFS cases have minimal prolapse).

How uterine prolapse may cause anterior rectal intussusception

Examination of *Figure 11* indicates how the attachment of USLs to the lateral wall of the rectum can cause intussusception in women who have uterine prolapse. As USLs lengthen, they splay laterally, causing the anterior rectal wall to also elongate laterally; such stretching weakens the rectal wall structurally. Its collagen concentration lessens and the anterior rectal wall invaginates to cause intussusception (11).

Conclusions

The structural basis of the Integral Theory is holistic. Four main pelvic muscles interact holistically with five main pelvic ligaments to maintain pelvic organ structure and function. As the vagina is a structurally weak organ, the support it provides to the bladder base is contingent on being stretched by opposite pelvic muscle forces with its main role being to transmit muscle forces to facilitate continence, evacuation and control of urgency. The vagina should not be excised as it cannot regenerate and, therefore, it should be conserved. The ligaments provide the main structural support for the organs and are the most vulnerable part of the anatomical system to injury because their structural collagen can be weakened during labour and collagen loss after the menopause due to collagen breakdown. Consequently, collagen loss is the main cause of organ prolapse and LUTS. By strengthening damaged ligaments, whether surgically or non-surgically, symptoms and prolapse can be improved or cured. The principal cause of dysfunction in older women is collagen loss in the ligaments; therefore, collagen-creating techniques are advised. Neoligaments can be created with precisely inserted tapes. Alternatively, ligaments can be strengthened by plicating them with wide-bore No. 2 or No. 3 polyester sutures.

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Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All clinical procedures described in this study were performed in accordance with the ethical standards of the institutional and/or national research committee(s) and with the Helsinki Declaration (as revised in 2013). Written informed consent was obtained from the patients for the publication of this article, accompanying images and videos. Human participation in the videos was by patient permission on the basis it was deidentified.

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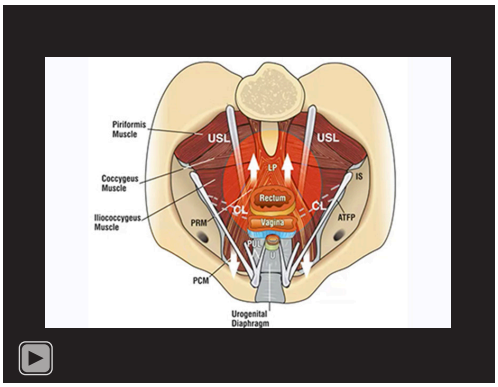
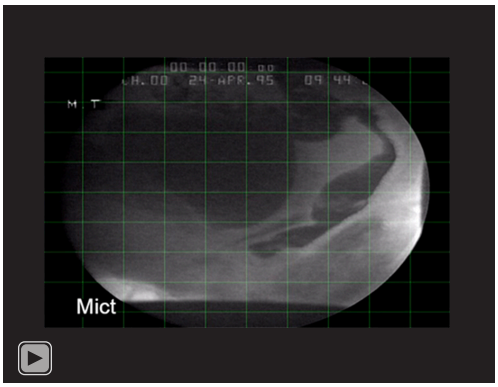
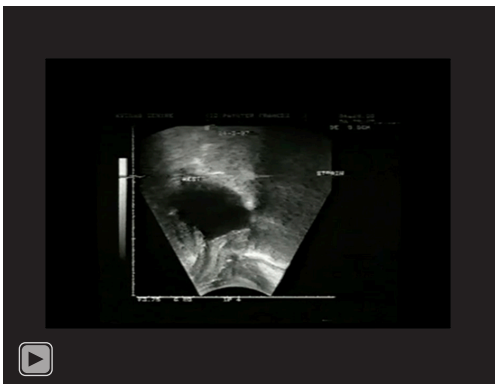
Supplementary



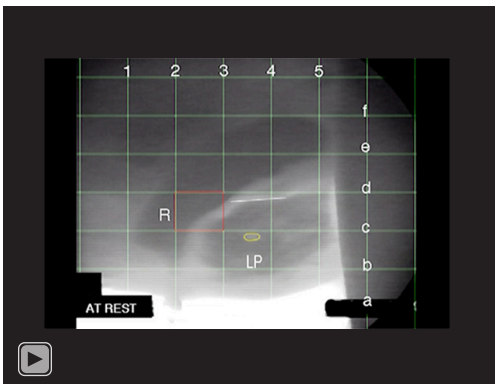
Video S1 Video abstract.



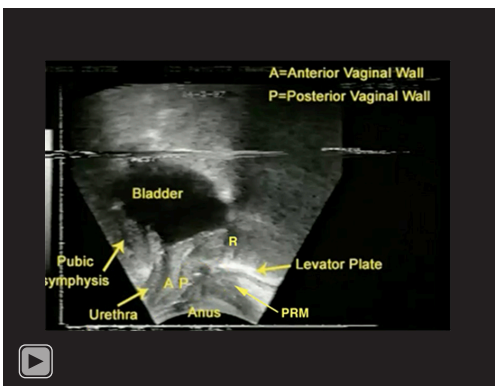
Video S4 Micturition PCM relaxes, LP/LMA open out the posterior urethral wall.



Video S2 Bladder closure US Three directional forces close the urethra distally and at the bladder neck.



Video S5 Defecation PRM relaxes. LP/LMA open out the anorectal angle.



Video S3 Anorectal closure US Three directional forces and PRM close the anorectal angle.

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