Review

A practical update on functional and dysfunctional anatomy of the female pelvic floor - Part 1 Function

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Abstract: Background The Integral Theory System considers pelvic organ prolapse (POP), pain, bladder & bowel dysfunctions to be mainly caused by laxity in up to 5 suspensory ligaments and their vaginal attachments. *Aim* To define the role of ligaments in normal function (Part1), then dysfunction and principles of surgical cure (Part 2). *Methods* The role of pelvic ligaments and muscles in normal bladder & bowel closure, evacuation, central and peripheral neurological control is analysed. *Results* Normal function Ligaments stretch minimally, vagina stretches extensively during coughing, straining, squeezing, micturition, defecation. Competent ligaments suspend organs and act as insertion points for 3 striated muscle forces. These act in opposite directions to close and open urethra & anorectum, stretch organs to prevent inappropriate activation of micturition and defecation reflexes. Dysfunction Ligaments must be competent, otherwise the muscles which contract against them lengthen and weaken. A cascade of dysfunctions follow from elongated ligaments: prolapse; muscles cannot close urethral and anal tubes (incontinence) open them (emptying problems) or stretch organs sufficiently to support stretch receptors which may fire off prematurely to activate the micturition reflex (urge incontinence, frequency, nocturia) or defecation reflex (fecal incontinence). *Conclusions* Part 1 demonstrated that competent ligament insertion points are required for the 3 directional forces which control mechanical closure and evacuation and the neurological feedback mechanisms for defecation and micturition reflexes. Lengthening of the sarcomere due to ligament laxity was considered the ultimate link between loose ligaments and dysfunctions in these organs.

Keywords TFS; Integral Theory; Bladder function; Bowel function; Pelvic ligament ; Sarcomere; Vagina; Stress incontinence; Chronic pelvic pain; OAB; Nocturia; Fecal incontinence.

INTRODUCTION

"Precise, almost mathematical knowledge of anatomy is a highly fertile source of surgical applications, suggesting new techniques and helping to perfect and simplify existing surgical methods, making them less mutilating and more benign and, in short, raising surgery to the rank of true science."

It is a fundamental truth that an accurate knowledge of anatomy is a pre-requisite for any surgery to any part of the human body. In conceptualizing this paper, we have been guided by the writings of the great Spanish Anatomist/Urologist Salvador Gil-Vernet (1892-1987) [1] and our own practical experience of application of the Integral Theory System over a collective period of more than 60 years.

STRUCTURE

Five main ligaments suspend the organs from the pelvic girdle. They are pubourethral (PUL), arcus tendineus fascia pelvis (ATFP), cardinal (CL), uterosacral (USL) and the deep transversus perinei portion of the perineal body (PB), figs 1, 2. A 6th ligament, external urethral ligament (EUL) attaches the external urethral meatus to the anterior surface of the pubic symphysis. It mainly controls urethral mucosal sealing[2].

It is the ligaments which provide suspensory strength. The main structural component of ligaments is cross-bonded collagen 1. According to Yamada[3], the breaking strain of ligaments is approximately 300 mg/mm^2. Suspensory ligaments do not stretch significantly during the effort of closure and micturition. This is evident on simple inspection of PUL and USL in the dynamic xrays, fig. 3.

The vagina is a weak elastic organ, breaking strain 60 mg/mm^2 [3]. Its elasticity permits the independent function of the 3 opposite muscle forces (arrows), fig. 3[4]. The vagina's elastic function is self-evident on simple inspection of fig. 3: the vagina is stretched significantly during urethral closure (straining) and micturition. Though the vagina helps to support the bladder, fig. 3, its role cannot be primarily structural as its breaking strain is only 60 mg/mm^2, a consequence of the predominance of collagen 3, a more elastic, but weak collagen. Structurally, the vagina acts like an (elastic) plaster board of a domestic ceiling, with cardinal ligaments, ATFP and cervical ring acting as the joists.

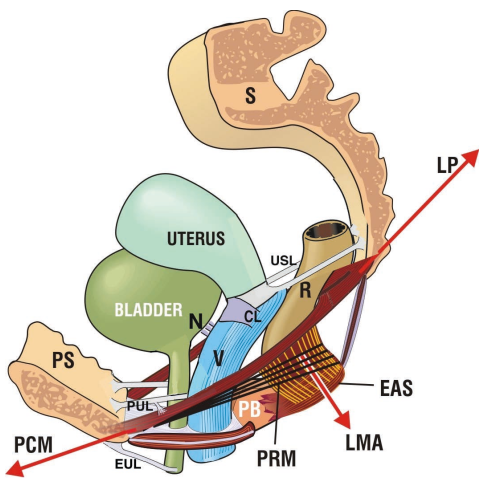

Figure 1. The relationship of ligaments, muscles and function.
The 5 ligaments which suspend the organs PUL= pubourethral ligament; CL=cardinal ligament; USL= uterosacral ligament; PB= perineal body. ATFP = arcus tendineus fascia pelvis); EUL = external urethral ligament is a 6th ligament which attaches the external meatus to the anterior surface of pubic symphysis (PS);
Forward acting muscles: m.pubococcygeus (PCM), m.puborectalis (PRM). PCM contracts against the pubourethral ligament (PUL). PRM contracts only against symphysis pubis.
Backward acting muscles: levator plate (LP) contracts backwards against PUL anteriorly; LMA contracts solely downwards against USLs . N=bladder stretch receptors; R=rectum; EAS=external anal sphincter; PS=pubic symphysis; S=sacrum.

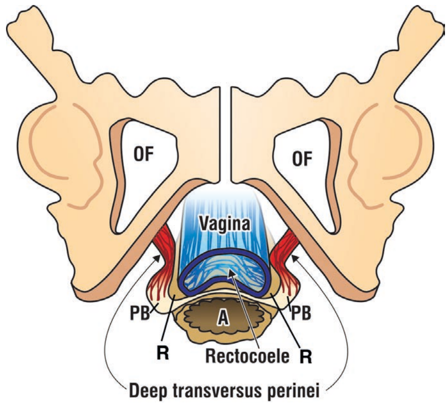

Figure 2. Deep transversus perinei ligaments[3] attach perineal body 'PB' to the descending ramus.
In this figure, the ligaments are elongated. PBs have been separated into two parts during childbirth, by stretching of their central part. This causes the rectum to protrude into the vagina as a rectocele.

The muscles The vagina and rectum rest on the pelvic floor muscles. There are four directional striated muscles vectors, fig1; two are forward acting: m.pubococcygeus (PCM), m.puborectalis (PRM). PCM is attached to distal vagina and contracts forwards against the pubourethral ligament (PUL). PRM contracts only against symphysis pubis. There are two posterior vectors (arrows, fig1): levator plate (LP) and conjoint longitudinal muscle of the pelvis (LMA). LP is attached to the posterior wall of rectum; it contracts backwards against PUL; LMA inserts into the anterior portion of LP proximally and the external anal sphincter distally; it contracts solely downwards against USLs, figs 1,3.

Muscle function
The opposite directional forces, figs 2&3, have three main functions.
1. They create shape and strength of the organs [5].
2. They close the urethral and anal tubes (continence) and help to empty them during micturition and defecation[4].
3. They stretch the vagina to support the bladder stretch receptors 'N', and tension USLs to support the nerve ganglions in the uterosacral ligaments[4].

FUNCTION

A summary of the role of the suspensory ligaments in bladder and anorectal function and dysfunction
The Integral Theory (IT) states that pelvic organ prolapse, symptoms of chronic pelvic pain, bladder and bowel dysfunction are mainly caused by laxity in 5 suspensory ligaments. The ligaments have a dual function: they suspend the organs and act as insertion points for three oppositely acting muscle forces. Lax ligaments weaken these muscle forces so they cannot adequately close the urethral or anal tubes (incontinence), evacuate them (constipation, bladder emptying), or tension the bladder and rectum sufficiently to prevent inappropriate activation of the micturition and defecation reflexes by their stretch receptors (urge incontinence of bladder & bowel). Up to 80% cure/improvement for the above conditions has been achieved following repair of one or more damaged ligaments using precisely positioned TFS tensioned tapes [6-13], Tables 1&2. The Integral Theory states "Repair the structure (ligaments) and you will restore the function". *The same operations are used for patients with major symptoms and minimal prolapse and major prolapse with no symptoms*[9].

Normal bladder function [4,5] (Fig. 3)
The bladder is a storage container for urine. Continence and evacuation are via the urethral tube. The bladder has 3 modes of function, fig. 3.
1. Resting closed mode, fig. 3, middle figure B. Urethral closure is maintained by vaginal elasticity, urethral elasticity/smooth muscle and slow twitch striated muscle contractions against PUL, 'S' acting forwards, backwards, downwards.
2. Effort closed mode fig. 3, left figure A. On effort, fast-twitch forward and backward forces act against PUL in opposite directions (arrows) to close urethra distally and proximally. A 3rd downward force (arrow) pulls down LP. This action rotates the bladder downwards to close (kink) bladder neck.

Table1: Lower und upper 95 %-confidence intervals for the observed relative frequencies of Prolapse, Urgency, Nocturia, Day time frequency, Dragging pain and Fecal incontinence.
Parallelly the results of testing the hypothesis Ho: $p \le p_0$ vs. H1: $p > p_0$ have entered.
' * ', ' # ' and ' / ' means significant p-values when p_0 is setting equal to 0.80, 0.75 and 0.60, respectively.
With other words these symbols depict that the observed cure rates are significantly higher than 0.80, 0.75 and 0.60 respectively (p < 0.05; Binomial Tests)

Variable	N	No of cured	observed cure rate (%)	95 %-lower CI	96 %-upper CI	Test results Ho: $p \le p_0$ vs. H1: $p > p_0$
Prolapse	278	257	92.10	0.891	0.952	*
Urgency	133	124	93.20	0.879	0.971	*
Nocturia	86	62	72.10	0.597	0.809	/
Day time frequency	132	120	90.10	0.935	0.999	*
Dragging pain	56	52	92.90	0.862	0.998	*
Fecal incontinence	52	46	88.50	0.798	0.977	#

TABLE 1. From Inoue et al.[6]

Variable	Number	Number cured	% cure	p value
Pelvic pain	25/79	20	80%	p<0.0001
*Nocturia	37/79	30	81%	p<0.0001
*Urge incontinence	42/79	37	88%	p<0.0001
*Frequency	49/79	42	85%	p<0.0001
Apical prolapse	79	74	93%	p<0.0001

TABLE 2. From Sekiguchi et al.[8]. N=79 - Mean age 68 years - 12 months data

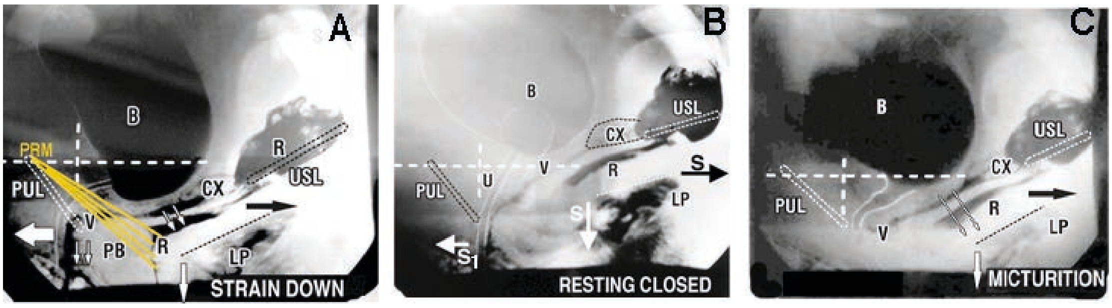

Figure 3 Normal bladder/bowel function Video xray, sitting position. Radio-opaque dye has been injected into the bladder, vagina, rectum, levator plate.
Middle figure B *At rest*, asymptomatic patient. Slow twitch directional forces 'S' (arrows) stretch the organs bidirectionally against pubourethral ligaments 'PUL' anteriorly and uterosacral ligament 'USL' posteriorly to close urethra and anus and to support the bladder base and rectal stretch receptors, preventing activation of the micturition and defecation reflexes. LP=levator plate; U=urethra; B=bladder; U=urethra; CX=cervix.
Left figure Straining A- *urethral closure* The ligaments do not stretch. They anchor the urethra, distal vagina and rectum. USL is angulated downwards. Fast twitch muscles stretch the distal vagina forwards (arrow) to close distal urethra; backward/downward vectors (arrows) contract against PUL and USL to stretch and rotate the proximal urethra, proximal vagina and rectum, around PUL to effect bladder neck closure.
Left figure Straining A -*anorectal closure* Puborectalis muscle (PRM, yellow) contracts. The same posterior vector forces (arrows) contract against PUL and USL, to stretch rectum 'R' around a contracted PRM and perineal body (PB) to close the anorectal angle and effect anorectal closure.
Right figure C *Micturition* The ligaments do not stretch. USL is angulated downwards. There is absence of a forward vector which has been relaxed by the micturition reflex. The vagina and rectum are stretched backwards and downwards. Fast twitch backward/downward vectors (arrows) contract against USL to open out the posterior wall of urethra, thus vastly reducing the internal resistance to flow.

3. Open (micturition) mode (fig. 3), right figure C. The forward arrow, S1, fig B, relaxes. Two fast-twitch directional forces* pull the posterior wall of urethra backwards. Bladder contracts to empty.
Note relative immobility of PUL and USL in fig. 3 and very significant stretching of the vagina in both closure and micturition.

Normal anorectal function

Bladder and bowel have similar closure and opening mechanisms[14].
The rectum is a storage container for feces. Continence and evacuation are via the anal tube. The anorectum has 3 modes similar to those of the bladder in fig. 3[14].
1. Resting closed mode, is maintained by slow twitch striated muscle contraction, organ elasticity/ smooth muscle (figs. 3&4).
2. Effort closed mode is activated by 3 fast-twitch directional forces during straining or coughing (fig. 3) (left frame). The uterosacral ligaments have a key role in anorectal closure. The USLs are attached to the lateral rectal walls by thin ligamentous attachments. LP stretches the rectum backwards against PUL to tension it prior to LMA contraction, fig4. LMA contracts against USL to pull down the anterior part of LP. This downward angulation rotates the rectum around a contracted puborectalis (PRM) to 'kink' the rectum and close the anorctal angle[14]. If either PUL or USL are loose, closure may not occur (fecal incontinence 'FI'). Hocking reported cure of double incontinence USI and FI with repair only of PUL with a midurethral sling[15]. The Kamakura group reported cure of FI with a cardinal/ uterosacral sling operation Table 1
3. Open (defecation) mode is an active process[14]. Defecation is activated by 3 fast-twitch directional forces, LP/LMA posteriorly, fig4 and a forward force possibly PCM or puboanalis acting on the anterior anal wall, fig. 5, forward arrow. With reference to fig. 5, the anterior border of the levator plate has been pulled downwards apparently by a downward vector. Levator plate 'LP' is clearly shown attaching to the posterior wall of rectum. It contracts backwards towards the coccyx. The posterior wall of the rectum has been stretched downwards and backwards (red arrows) apparently by the resultant of these two vectors, The anorectal angle 'ARA' descends into the light green rectangle at 45^o The opening extends all the way down the posterior wall of the anus. The anterior wall of rectum has been pulled forwards to further open out the anal canal.
The USLs have a key role in defecation. The USLs are attached to the lateral walls of rectum; the downward vector (arrow), fig. 5, contracts directly against the USLs during

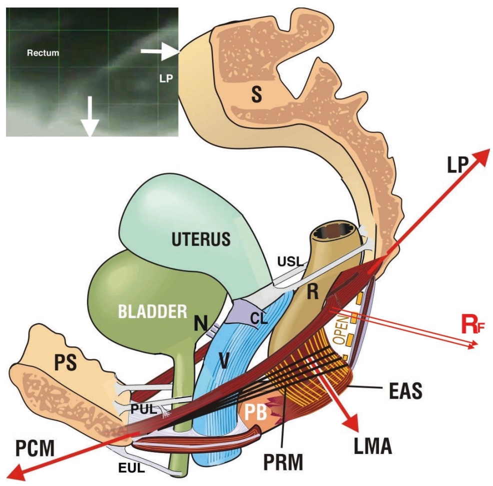

Figure 4 Anorectal closure and defecation
Closure (continence) LP/LMA stretch and rotate the rectum (R) around a contracted PRM to 'kink' the rectum closed. 'RF' is the resultant of the two forces LP/LMA and acts as the rotating vector to create the anorectal angle. See also 'straining' xray fig. 3.
Opening (defecation) PRM relaxes, LP/LMA (RF) contract to open out the anorectal angle ; rectum 'R' contracts to empty.The broken orange vertical lines behind the rectum 'R' indicate rectal position during "OPEN" mode (defecation) : Upper left corner X-ray myogram defecation mode. Anorectal angle opened out.

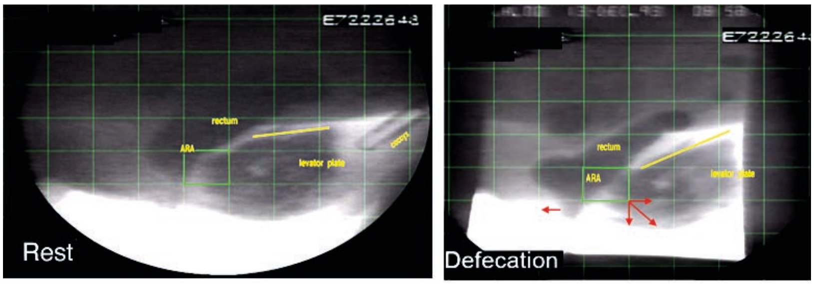

Figure 5. X-ray defecating procto-myogram
At rest The anorectal angle 'ARA' to the left of the green square is angled. The anus is closed. The superior surface of the levator plate muscle is almost horizontal.
Defecation mode ARA is opened out by backward and downward vectors LP/LMA (arrows). The anterior wall of anus is pulled forwards (arrow) further opening out the anal canal. Note the insertion of levator plate into the posterior wall of rectum. The resultant vector action (arrow) seems to be opening out ARA. The downward angulation of the anterior border of levator plate is identical with what happens during micturition[14]; conjoint longitudinal muscle of the anus (LMA) pulling down the anterior margin of levator plate (LP).

defecation. A loose USL will weaken the contractile strength of a striated muscle potentially leading to inability to properly close or evacuate. The patients senses this as "constipation: and the physician as "Obstructive Defecation syndrome' (ODS).

Control of the micturition, defecation reflexes and pain - According to the Integral Theory, urge incontinence, nocturia (OAB) even urodynamic 'detrusor overactivity' are expressions of a prematurely activated but otherwise normal micturition reflex[4]. This concept was urodynamically validated in 1993: it was demonstrated that the events which occur during micturition and the 'unstable bladder' ('OAB', 'DO') are identical[16]: 1 Sensation of urge; 2. Fall in proximal urethral pressure; 3. Rise in detrusor pressure: 4. Urine loss. The bidirectional stretching of the vagina (fig. 6), acts like a trampoline to support the stretch receptors 'N' at bladder base; as the hydrostatic pressure of urine rises, spindle cells in the oppositely acting muscles automatically cause the muscles to stretch the vagina to support 'N', thus preventing activation of the micturition reflex. A similar feedback system applies to the anorectum.
It is hypothesized that the nerve plexuses in the distal parts of the USLs, the Frankenhauser and Sacral plexuses, are similarly controlled: the opposite muscle stretching tensions the USLs to support the nerves preventing them from firing off.

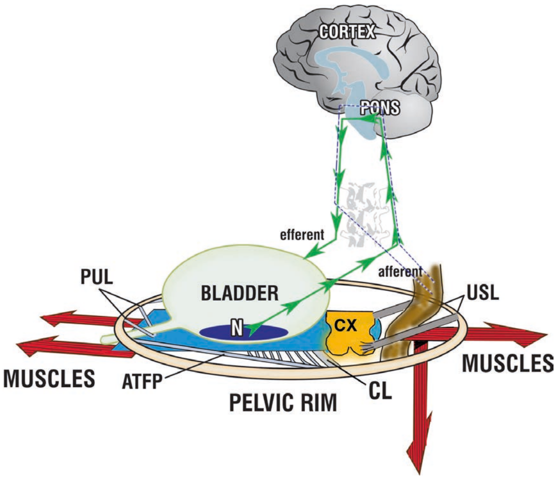

Figure 6. The trampoline analogy.
In the normal patient, the stretch receptors 'N' sense bladder fullness and send afferent signals to the cortex (green afferent arrows); afferent signals are controlled centrally and peripherally by opposite stretching of the vaginal membrane by muscle forces (arrows); the stretched vagina supports the hydrostatic pressure exerted by the urine column. At a critical point, the afferent signals (green arrows) activate the micturition reflex which causes the forward muscles to relax; the posterior muscles contract to open out the posterior urethral wall; the detrusor contracts to empty4. A similar feedback control system, opposite stretching of the posterior vectors and puborectalis supports the anorectal stretch receptors (continence). Increased afferent impulses (green arrows) activate the defecation reflex, relax puborectalis, contract the posterior vectors to open out the anorectal angle, contract the rectum to empty.

Gordon's Law- the ultimate pathway for understanding how ligament looseness may cause muscle dysfunction and symptoms.
Gordon's Law (fig. 7) is the key to understanding the causation of bladder and bowel function and dysfunction. It states *"A striated muscle contracts optimally over a short length only* ('E', fig. 7). If the ligaments against which the 3 vector muscles contract are firm, the muscles contract efficiently over a length 'E', fig. 7. However, *Lengthening the contractile length results in a rapid loss of contractile strength*."[17].
If the ligaments against which the three vector muscles contract lengthen by 'L", the muscles lengthen accordingly and their contractile strength weakens[4], from a nominal 80% to 30%, fig. 7.

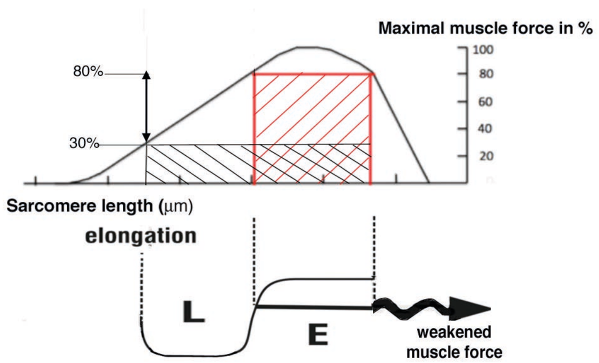

Figure 7. Gordon's Law.
A striated muscle contracts optimally over a short length only, 'E', red square. Lengthening the muscle 'L', results in a rapid loss of contractile force, black rectangle.

CONCLUSIONS

Part 1 examined the key role of competent ligament insertion points for the 3 directional forces which control normal bladder, bowel & nerve function. Part 2 builds on Part 1 to explain which ligaments may be causing the dysfunctions and how ligament shortening can reverse the cascade of events which led to the dysfunction

DISCLOSURES

Conflicts of Interest: None
IRB approval: Not required
Contributions to the article: Conceptualization writing: all authors; Figures Tables YS, HI
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REFERENCES

1. Gil-Vernet JM, Salvador Gil-Vernet, a pioneer in Urological Anatomy, Chaper in De Historia Urologiae Europeaeae Vol 24 2017, Eds. Van Kerrebroecke P, Schultheiss D, EAU History Office European Association of Urology, pp13-43.
2. Petros PE Chapter 2: The Anatomy and Dynamics of Pelvic Floor Function and Dysfunction, in The Female Pelvic Floor, Function, Dysfunction and Management According to the Integral Theory, Petros PEP, 3rd Ed 2010, Springer Heidelberg, pp17-77.
3. Yamada H. Aging rate for the strength of human organs and tissues. Strength of Biological Materials, Williams & Wilkins Co, Balt. (Ed) Evans FG. (1970); 272-280.
4. Petros PE & Ulmsten U. An Integral Theory of female urinary incontinence. Acta Obstetricia et Gynecologica Scandinavica, 1990; Supp.153; 69, 1-79.
5. Petros PE and Ulmsten U Role of the pelvic floor in bladder neck opening and closure: I muscle forces. Int J Urogynecol and Pelvic Floor. 1997; 8, 74-80
6. Inoue, H Kohata Y, Sekiguchi Y, Kusaka T,Fukuda T, Monnma M. The TFS minisling restores major pelvic organ prolapse and symptoms in aged Japanese women by repairing damaged suspensory ligaments – 12 - 48 month data, Pelviperineology 2015; 34: 79-83
7. Nakamura R,Yao M Maeda Y, Fujisaki A, Sekiguchi Y Outpatient mid-urethral tissue fixation system sling for urodynamic stress urinary incontinence: 3-year surgical and quality of life results Int Urogynecol J 2016 Open access DOI 10.1007/s00192-017-3341-4.
8. Sekiguchi Y1, Kinjo M, Maeda Y, Kubota Y. Reinforcement of suspensory ligaments under local anesthesia cures pelvic organ prolapse: 12-month results. Int Urogynecol J. 2014 Jun;25(6):783-9.
9. Petros PEP, Richardson PA TFS posterior sling improves overactive bladder, pelvic pain and abnormal emptying, even with minor prolapse –a prospective urodynamic study. (2010) Pelviperineology 29: 52-55
10. Inoue H , Kohata Y, Fukuda T, Monma M, et al Repair of damaged ligaments with tissue fixation system minisling is sufficient to cure major prolapse in all three compartments: 5-year data J. Obstet. Gynaecol. Res. 2017 doi:10.1111/jog.13413
11. Nakamura R, Yao M, Maeda Y, Fujisaki A, Sekiguchi Y. Outpatient mid-urethral tissue fixation system sling for urodynamic stress urinary incontinence: 3-year surgical and quality of life results Int Urogynecol J 2017 DOI 10.1007/s00192-017-3341-4
12. Sivaslioglu AA, Eylem U, Serpi A, et al. A prospective randomized controlled trial of the transobturator tape and tissue fixation minisling in patients with stress urinary incontinence: 5-year results. J Urol. 2012;188:194–9.
13. Nakamura R, Yao M, Maeda Y, Fujisaki A, Sekiguchi Y Retropubic tissue fixation system tensioned mini-sling carried out under local anesthesia cures stress urinary incontinence and intrinsic sphincter deficiency: 1-year data International Journal of Urology , 2017; doi: 10.1111/iju.13360
14. Petros P. E., Bush MB The same posterior muscle vectors act to open urethra and anus during micturition and defecation, Pelviperineology 2017; 36: 35-36
15. Ian W. Hocking Experimental Study No. 9: Double incontinence, urinary and fecal, cured by surgical reinforcement of the pubourethral ligaments Pelviperineology 2008; 27: 110.
16. Petros PE & Ulmsten U. Bladder instability in women: A premature activation of the micturition reflex. Neurourology and Urodynamics 12, 235-239 (1993).
17. Gordon AM, Huxley AF, Julian FJ. The variation in isometric tension with sarcomere length in vertebrate muscle fibres. J Physiol. 1966;184(1):170-92.

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