Published in final edited form as:

Int Urogynecol J. 2014 February ; 25(2): 197–203. doi:10.1007/s00192-013-2211-y.

Using stress MRI to analyze the 3D changes in apical ligament geometry from rest to maximal Valsalva: a pilot study

Jiajia Luo,

Pelvic Floor Research Group, University of Michigan, Ann Arbor, MI, USA; Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI, USA; Biomechanics Research Laboratory, 2350 Hayward St. GG Brown Building 3212, Ann Arbor, MI 48109, USA

Cornelia Betschart,

Pelvic Floor Research Group, University of Michigan, Ann Arbor, MI, USA; Department of Gynecology, University Hospital of Zurich, Zurich, Switzerland; Division of Gynecology, Department of Obstetrics and Gynecology, University of Michigan, Ann Arbor, MI, USA

Luyun Chen,

Pelvic Floor Research Group, University of Michigan, Ann Arbor, MI, USA; Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI, USA

James A. Ashton-Miller, and

Pelvic Floor Research Group, University of Michigan, Ann Arbor, MI, USA; Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI, USA

John O. L. DeLancey

Pelvic Floor Research Group, University of Michigan, Ann Arbor, MI, USA; Division of Gynecology, Department of Obstetrics and Gynecology, University of Michigan, Ann Arbor, MI, USA

Abstract

Introduction and hypothesis—A method was developed using 3D stress magnetic resonance imaging (MRI) and was piloted to test hypotheses concerning changes in apical ligament lengths and lines of action from rest to maximal Valsalva.

Methods—Ten women with (cases) and ten without (controls) pelvic organ prolapse (POP) were selected from an ongoing case-control study. Supine, multiplanar stress MRI was performed at rest and at maximal Valsalva and was imported into 3D Slicer v. 3.4.1 and aligned. The 3D reconstructions of the uterus and vagina, cardinal ligament (CL), deep uterosacral ligament (USL_d), and pelvic bones were created. Ligament length and orientation were then measured.

Results—Adequate ligament representations were possible in all 20 study participants. When cases were compared with controls, the curve length of the CL at rest was 71 ±16 mm vs. 59±9

© The International Urogynecological Association 2013

jjluo@umich.edu.

Conflicts of interest Dr. John O. DeLancey and Dr. James A. Ashton-Miller have no directly related conflicts of interest for this study. The University of Michigan received funding from Johnson & Johnson, American Medical Systems, Kimberly-Clark Corporation, Proctor & Gamble, and Boston Scientific Corporation as partial salary support for research unrelated to the topic of this paper. They received an honorarium and travel reimbursement for giving an invited research seminar at Johnson & Johnson. Dr. Jiajia Luo has no directly related conflicts of interest for this study, but his doctoral studies were partially funded by American Medical Systems and Kimberly Clark Corporation unrelated to the topic of this paper, and he currently receives research support from Boston Scientific Corporation unrelated to the topic of this paper.

Dr. Luyun Chen received research support from American Medical Systems unrelated to the topic of this paper.

Dr. Cornelia Betschart received research support from the Swiss National Science Foundation unrelated to the topic of this paper.

mm ($p = 0.051$), and the USL_d was 38 ± 16 mm vs. 36 ± 11 mm ($p = 0.797$). Similarly, the increase in CL length from rest to strain was 30 ± 16 mm vs. 15 ± 9 mm ($p = 0.033$), and USL_d was 15 ± 12 mm vs. 7 ± 4 mm ($p = 0.094$). Likewise, the change in USL_d angle was significantly different from CL ($p < 0.001$).

Conclusions—This technique allows quantification of 3D geometry at rest and at strain. In our pilot sample, at maximal Valsalva, CL elongation was greater in cases than controls, whereas USL_d was not; CL also exhibited greater changes in ligament length, and USL_d exhibited greater changes in ligament inclination angle.

Keywords

Pelvic organ prolapse; Apical support; Cardinal ligament; Uterosacral ligament; 3D model

Introduction

Pelvic floor dysfunction results in 11 % of women in the USA undergoing surgery [1] during their life span. More than 200,000 operations are performed each year for prolapse [2], and the annual estimated cost for these operations exceeds US \$1 billion [3]. The status of apical support provided by the cardinal (CL) and the uterosacral ligament (USL) is thought to be one of the main factors related to pelvic organ prolapse (POP) [4]. However, data concerning changes in CL and USL lengths and lines of action in living women are sparse. We recently developed a static technique for assessing ligament geometry using magnetic resonance imaging (MRI) [5]. We developed a dynamic technique for comparing resting and straining geometry through what we call a stress MRI, and we piloted this technique to test the null hypotheses that there are no differences between the CL and deep USL (USL_d) when comparing women with and without prolapse for: (a) ligament length at rest, (b) ligament elongation (length change from rest to Valsalva), and (c) ligament orientation relative to a reference axis.

Materials and methods

This study was a secondary analysis of data from an ongoing case-control study of POP. We built specific 3D models for each study participant using MRI scans of the CL and USL_d at rest and during Valsalva to establish ligament length and angle in each condition. MRI scans of ten women with POP (cases) and ten with normal support (controls) were selected from an ongoing University of Michigan case-control study of POP that was approved by the institutional review board (IRB # 1999-0395). Only women with a uterus were considered.

The prolapse group included five cases of anterior vaginal prolapse (AVP, or cystocele) and five of posterior vaginal prolapse (PVP^R, or rectocele). All cystocele cases had an anterior vaginal wall (AVW) extending at least 1 cm below the hymen based on the POP Quantification system (POP-Q) and had symptoms of bulging or protrusion. For patients with cystocele to be included in the study, the cystocele had to be the predominant aspect of the prolapse and extend at least 1 cm lower than the most dependent part of the posterior vaginal wall (PVW) or the uterus/apex. Similarly, all patients with rectocele had PVP, with the PVW extending at least 1 cm below the hymen based on the POP-Q and symptoms of bulging or protrusion. In order for these patients to be included, the rectocele had to be the predominant aspect of the prolapse and extend at least 1 cm lower than the most dependent part of anterior wall or the uterus/apex. Women with a uterine-predominant prolapse and enteroceles were excluded. No patient had previously undergone prior pelvic floor surgery. To identify cases, starting from the most recent scans, we worked backward, sequentially examining images and selecting MRI sets that would allow model construction and

measurements. Twenty scans of women with cystocele or rectocele that had to be reviewed to achieve our study sample were evaluated for inclusion according to the following criteria required for adequate model construction: prolapse size consistent with clinical examination (POP-Q), ability to hold Valsalva for the entire 17 s of scan acquisition, freedom from significant motion artifact, inclusion of all necessary structures and landmarks, evenly distributed intravaginal ultrasound gel, and sufficient definition of vaginal walls to allow models to be made. Ten of 20 scans were selected as cases based on above criteria. Similarly, matched controls (who had an age difference within ± 3 years, number of vaginal deliveries within ± 1 , and of similar race) had to meet the above criteria except for prolapse. Controls were recruited by newspaper and radio advertisements for healthy volunteers, were asymptomatic, and had normal vaginal support, with all POP-Q points < -1 cm.

The technique for stress MRI is described in our previous work [6-8]. Briefly, each participant underwent pelvic floor MRI to obtain supine, multiplanar, 2D, fast-spin, proton-density MRI both at rest and during maximal Valsalva using a 3-T superconducting magnet (Philips Medical Systems Inc, Bothell, WA, USA) with version 2.5.1.0 software. Each set of 30 images taken with the study participant at rest were serially obtained in axial, sagittal, and coronal slices, with 20×20 -cm fields of view (FOV), 4-mm slice thickness, and a 1-mm gap between slices. During maximal Valsalva, 14 images were obtained at the same three serial planes, with 36×36 -cm FOV, 6-mm slice thickness, and 1-mm gap. In order for images to be considered adequate, they had to provide visualization of both left and right vaginal margins and the full scope of the cardinal and uterosacral ligaments up to the upper limit of the greater sciatic foramen.

Axial, sagittal, and coronal images were imported into 3D Slicer 3.4.2009-10-15 (Brigham and Women's Hospital, Boston, MA, USA) imaging software. Axial, sagittal, and coronal images taken with the participant at rest were manually aligned first with fixed landmarks, such as pubic bone, hip joint, and sacrum. Three-dimensional reconstructions of the uterus and vagina, CL, USL_d, and pelvic bones were then created in 3D Slicer based on descriptions in the literature [9]. The USL_d was traced on axial MRI with its origins from sacrum and sacrospinous ligament-coccygeus muscle and insertions to the genital tract. The CL was traced on coronal images with its origins from the pelvic side wall at the top of the greater sciatic foramen to its insertion on the genital tract centered on the cervix and upper vagina. Figure 1 illustrates the 3D-model-generation process. Models were compared with the original images to check fidelity.

To analyze CL and USL_d deformation under load, 3D models of midsagittal pubic symphysis (PS) and sacrum were reconstructed using MRIs from maximal Valsalva to allow the pelvic bones of the resting images and Valsalva images to be aligned with one another. This registration information was then applied to the soft tissue images, making it possible to align the midsagittal images at strain with those at rest. Axial and coronal images at strain were then manually aligned with midsagittal images at strain using bony landmarks, as above. The lateral view of rest and strain models of one normal and one prolapse individual are shown in Fig. 2. The PS to the ischial spines (P-IS) line [7, 8], is shown for spatial reference. The models and anatomical landmarks were imported into Imageware v.13 (Siemens Product Lifecycle Management Software Inc, Plano, TX, USA), as previously described [5]. The model and measurement strategy are shown in Fig. 3 based on the model from MRI scans with the individual at rest. Angles of the 3D lines of action of the four ligaments were determined by connecting the center of the origin and insertion points (Fig. 3a, b) and measuring the angle between these lines and the vertical-body axis (Fig. 4). Straight-and curved-line lengths were measured by constructing a cross section for each ligament by cutting the model with a plane defined by its line of action and genital origin point (Fig. 3; for more details of the analysis technique, *see* Chen et al. [5]). The best-fit

curve of the ligament was then made by connecting the center line of the cross section. Ligament curve length was measured, and the distance between origins and insertions was assessed as a straight-line length (Fig. 3). The ratio between these two measures is a proxy for the degree of curvature present. Measurement for ligaments under maximal Valsalva was then executed following the same strategy.

Descriptive statistical analysis and two-sided Student's *t* test were applied using a *p* value of 0.05 as significant. For nonparametric variables, two-sided Wilcoxon rank-sum test was applied using a *p* value of 0.05 as significant.

Results

The two groups were similar with respect to age, body mass index (BMI), vaginal parity, and race. When cases were compared with controls, median parity was 2 vs. 2 (*p* = 0.724, Wilcoxon rank-sum test), mean ± standard deviation (SD) age was 55.3 ± 8.1 vs. 53.7 ± 4.5 years (*p* = 0.600), BMI was 27.2 ± 3.7 vs. 26.5 ± 5.1 kg/m² (*p* = 0.734), and race was 90 % vs. 90 % Caucasian, respectively. Mean ± SD POP-Q values of patient with cystocele or rectocele and control individuals were: Aa, 1.4 ± 1.1, -1.0 ± 1.4, -1.9 ± 0.9; Ba, 2.6 ± 1.5, -1.4 ± 0.9, -1.9 ± 0.9; C, -0.8 ± 3.4, -5.5 ± 1.6, -7.0 ± 1.3; D, -5.8 ± 2.6, -7.3 ± 1.3, -9.3 ± 1.2; Ap, -0.6 ± 1.7, 1.6 ± 0.5, -2.2 ± 0.4; Bp, -0.6 ± 1.7, 1.8 ± 0.8, -2.2 ± 0.4.

Figure 4 illustrates the average straight length and angle of each ligament with respect to the vertical-body axis at rest and maximal Valsalva. At rest, CL straight length was 65 ± 15 mm for cases and 50 ± 8 mm for controls; at maximal Valsalva, it was 93 ± 24 mm for cases and 59 ± 11 mm for controls. Similarly, at rest, the USL_d straight length was 35 ± 14 mm for cases and 33 ± 9 mm for controls; at maximal Valsalva, it was 45 ± 13 mm for cases and 35 ± 5 mm for controls. In cases, the CL elongated 16 mm more than did the USL_d, and in controls, the CL elongated 4 mm more than did the USL_d. Comparing cases with controls in relative (percentage) straight-length elongation, CL elongated 47 % ± 32 % vs. 21 % ± 23 %, and USL_d elongated 51 % ± 56 % vs. 26 % ± 23 %.

The resting curve length of ligaments did not differ between groups (CL, *p* = 0.051; USL_d, *p* = 0.797; Fig. 5). However, the straining curve length differed significantly by group (CL, *p* = 0.003; USL_d, *p* = 0.037). The CL during strain was longer than at rest in both cases (*p* < 0.001) and controls (*p* = 0.002). The CL lengthened from rest to strain by 30 ± 16 mm in cases (*p* = 0.033) and 15 ± 9 mm in controls. No differences were found for USL_d. Whether at rest or at strain, the CL was substantially longer than the USL_d in all comparisons (*p* < 0.001). Comparing cases with controls in relative (percentage) curve-length elongation, CL elongated 45 % ± 31 % vs. 28 % ± 18 %, and USL_d elongated 53 % ± 55 % vs. 27 % ± 26 %. Furthermore, at rest, the average ratio of curve length over straight length for CL at rest was 1.19 for cases and 1.10 for controls, whereas the corresponding values at maximal Valsalva were 1.26 and 1.09, respectively. At rest, the average ratio of curve length over straight length of the USL_d was 1.09 for cases and 1.09 for controls; at maximal Valsalva, it was 1.13 for cases and 1.10 for controls.

Upon examining the orientation of ligaments at rest and at strain (Fig. 4), it can be seen that the USL_d rotated about its origin. We therefore quantified ligament axis relative to body axis from rest to strain and found that the angle change for the USL_d (cases, -32° ± 18°; controls -23° ± 17°) were greater than that for the CL (cases, -6° ± 5°; controls -7° ± 10°; Figs. 4 and 6). The angles for both ligaments changed significantly for all comparisons except CL (CL, *p* = 0.003 for cases, but *p* = 0.07 for controls; USL_d, *p* < 0.001 for cases, and *p* = 0.002 for controls). In addition, for both resting and straining states, the CL angle was smaller than the USL_d angle in all comparisons (*p* < 0.001).

Discussion

In these 3D stress MR-based models specifically designed for each individual, we demonstrated that CL and USL_d length and angle altered between rest and straining states in both cases and controls. Concerning our original hypotheses, the length of ligaments at rest was not significantly different between cases and controls. However, the other hypotheses were rejected in that CL ligament elongation from rest to Valsalva was greater in cases than controls, whereas this was not the case for USL_d. In addition, the CL incurred greater changes in length, whereas the USL_d displayed greater changes in angle.

Previous research [6, 8] shows that the downward translation of the upper part of the vagina is one of the main characteristics of both cystocele and rectocele. In addition, the CL is relatively vertical in the standing position, whereas the USL_d is more likely to be dorsally directed [5] (*see* “Results”). The direction of descent is influenced by the presence of the levator plate. These findings might help explain why the CL is under larger tensile force than the USL_d when the apex is loaded with an arbitrary force [5]. Hence, the change in CL with prolapse is greater than that of the USL_d. However, in the study reported here, the USL_d angle change with prolapse was larger than that of the CL, which also helps explain the behavioral difference in tension distribution between the two ligaments.

The CL and USL_d are not like skeletal ligaments that consist of homogenous collagenous tissue. Rather, they are visceral ligaments and most like a mesentery, comprising varying combinations of blood vessels, nerves, smooth muscle, and areolar tissue [10-13]. They both support the cervix but have distinctly different compositions [10, 11]. In addition, they have different lines of action [5], with the CL being relatively vertical in the standing posture and the USL_d being more dorsally directed. It has been possible to study these ligaments in cadavers, but understanding how they change in living women has only now become possible by their identification on MRI [9, 14]. The degree to which each ligament lengthens can help determine the nature and direction of the loss of apical support. The potential clinical relevance of different supporting vectors might be illustrated by differences in outcome depending on different directions of apical support. For example, in a study by Maher et al. [15], sacrospinous colpopexy was associated postoperatively with a higher rate of cystocele (14 %) than of abdominal sacral colpopexy (7 %). The reverse was true for rectocele, which was less frequent in the sacrospinous group (7 %) than in the abdominal group (17 %). This could potentially be consistent with a hypothesis that the more dorsal location of the sacrospinous suspension puts the anterior wall at risk, and the more vertical sacral colpopexy puts the posterior wall at risk. This type of analysis may help us to understand the consequences of these and other apical suspension techniques, but clinical outcome studies will, of course, be needed to make final decisions about treatment decisions. Knowing how much each ligament changes under load in women with prolapse compared with those with normal support will lead to a better understanding the problems discussed in this paper.

Although we believe that relative and absolute ligament elongation values provide useful information, absolute elongation should be of direct use to the surgeon. Surgeons use apical ligaments in repair, shortening the CL and using the USL to resuspend the vagina as a strategy to elevate the vaginal apex [16, 17]. Our study provides data concerning how much each ligament lengthens and the amount of elevation needed to return them to normal. This could help in developing scientific strategies to improve surgical treatment. For example, it might help in determining how different surgical suspension vectors (e.g., sacral colpopexy vs uterosacral suspension vs sacrospinous ligament suspension) affect postoperative outcomes.

This study has several limitations. First, it was based on a small sample of women with distal posterior and anterior predominant prolapse versus women with normal support. In this pilot study, we chose these two different prolapse types to assure that the assessment technique could be carried out in both types. We recognize that there are many different types of prolapse. Now that a technique is available and preliminary data established on which to conduct a power analysis, further research is needed to establish differences between different types of prolapse. Some differences we found did not reach statistical significance due to our small sample size, but they may do so with larger samples. It would be worth studying women who have uterine prolapse in association with cystocele or rectocele to gain an understanding of the mechanisms underlying more complicated types of prolapse. Second, MRIs were obtained with the women in the supine position. There might be small changes in ligament lengths and angles in the standing position. However, these studies are similar to the supine pelvic examination with Valsalva, which is used by clinicians to examine the prolapse, and we feel that with adequate Valsalva, prolapse can be achieved at the maximal extent. Third, although the manual tracing of CL and USL_d is based on our understanding of the anatomy and verified by the senior author, some variation might be expected in the results by other examiners. Fourth, we cannot blind the individuals making the measurements for either cases or controls, as prolapse images are visible.

This study is a first step toward creating a method for analyzing the changes in CL and USL_d from rest to maximal Valsalva in women with and without POP, providing a comparison of ligament length and angle. To enhance the level of precision, future studies should be based on larger sample sizes and include more complex types of prolapse.

Acknowledgments

We gratefully acknowledge support from the National Institutes of Health, Office for Research on Women's Health, Specialized Center of Research: Sex and Gender Factors Affecting Women's Health, Grant P50 HD 044406, and NIH R01 HD 038665.

References

1. Olsen AL, Smith VJ, Bergstrom JO, Colling JC, Clark AL. Epidemiology of surgically managed pelvic organ prolapse and urinary incontinence. *Obstet Gynecol.* 1997; 89(4):501–506. [PubMed: 9083302]
2. Boyles SH, Weber AM, Meyn L. Procedures for pelvic organ prolapse in the United States, 1979–1997. *Am J Obstet Gynecol.* 2003; 188(1):108–115. [PubMed: 12548203]
3. Subak LL, Waetjen LE, van den Eeden S, Thom DH, Vittinghoff E, Brown JS. Cost of pelvic organ prolapse surgery in the United States. *Obstet Gynecol.* 2001; 98(4):646–651. [PubMed: 11576582]
4. Summers A, Winkel LA, Hussain HK, DeLancey JO. The relationship between anterior and apical compartment support. *Am J Obstet Gynecol.* 2006; 194(5):1438–1443. [PubMed: 16579933]
5. Chen L, Ramanah R, Hsu Y, Ashton-Miller JA, DeLancey JO. Cardinal and deep uterosacral ligament lines of action: MRI based 3D technique development and preliminary findings in normal women. *Int Urogynecol J.* 2013; 24(1):37–45. [PubMed: 22618207]
6. Larson KA, Hsu Y, Chen L, Ashton-Miller JA, DeLancey JO. Magnetic resonance imaging-based three-dimensional model of anterior vaginal wall position at rest and maximal strain in women with and without prolapse. *Int Urogynecol J.* 2010; 21(9):1103–1109. [PubMed: 20449568]
7. Larson KA, Luo J, Guire KE, Chen L, Ashton-Miller JA, DeLancey JO. 3D analysis of cystoceles using magnetic resonance imaging assessing midline, paravaginal, and apical defects. *Int Urogynecol J.* 2012; 23(3):285–293. [PubMed: 22068322]
8. Luo J, Larson KA, Fenner DE, Ashton-Miller JA, DeLancey JO. Posterior vaginal prolapse shape and position changes at maximal Valsalva seen in 3-D MRI-based models. *Int Urogynecol J.* 2012; 23(9):1301–1306. [PubMed: 22527556]

9. Ramanah R, Berger MB, Chen LY, Riethmuller D, DeLancey JOL. See it in 3D! Researchers examined structural links between the cardinal and uterosacral ligaments. *Am J Obstet Gynecol.* 2012; 207(5):437.e1–437.e7. [PubMed: 22999154]
10. Campbell RM. The anatomy and histology of the sacrouterine ligaments. *Am J Obstet Gynecol.* 1950; 59(1):1–12. [PubMed: 15399622]
11. Range RL, Woodburne RT. The gross and microscopic anatomy of the transverse cervical ligament. *Am J Obstet Gynecol.* 1964; 90:460–467. [PubMed: 14217646]
12. Cole EE, Leu PB, Gomelsky A, Revelo P, Shappell H, Scarpero HM, Dmochowski RR. Histopathological evaluation of the uterosacral ligament: is this a dependable structure for pelvic reconstruction? *BJU Int.* 2006; 97(2):345–348. [PubMed: 16430644]
13. Ramanah R, Berger MB, Parratte BM, DeLancey JO. Anatomy and histology of apical support: a literature review concerning cardinal and uterosacral ligaments. *Int Urogynecol J.* 2012; 23(11): 1483–1494. [PubMed: 22618209]
14. Tunn R, DeLancey JO, Quint EE. Visibility of pelvic organ support system structures in magnetic resonance images without an endovaginal coil. *Am J Obstet Gynecol.* 2001; 184(6):1156–1163. [PubMed: 11349182]
15. Maher CF, Qatawneh AM, Dwyer PL, Carey MP, Cornish A, Schluter PJ. Abdominal sacral colpopexy or vaginal sacrospinous colpopexy for vaginal vault prolapse: a prospective randomized study. *Am J Obstet Gynecol.* 2004; 190(1):20–26. [PubMed: 14749629]
16. Lee, RA. *Atlas of gynecologic surgery.* WB Saunders; Philadelphia: 1992.
17. Shull BL, Bachofen C, Coates KW, Kuehl TJ. A transvaginal approach to repair of apical and other associated sites of pelvic organ prolapse with uterosacral ligaments. *Am J Obstet Gynecol.* 2000; 183(6):1365–1374. [PubMed: 11120498]

Fig. 1. Creating the 3D model: Coronal magnetic resonance image (MRI) showing the cardinal ligament (**a**; blue arrow) and with outline (**b**). Model of cardinal ligament (**c**, blue) shown in slightly skewed coronal image. Axial image showing the deep uterosacral ligament (**d**; green arrow) and with outline (**e**). Model of deep uterosacral ligament **f**; green) shown in the same view angle as (**c**). Midsagittal image with outline (**g**) and 3D model (**h**) of uterus and vagina. Model without image (**i**) shown in same view angle as (**c**). Cx cervix, P pubic symphysis, B bladder, Ut uterus, V vagina, S sacrum (© DeLancey)

Fig. 2.

Normal and prolapse ligament comparison under resting and maximal Valsalva. Left side view of 3D models of one healthy individual at rest (**a**) and at maximal Valsalva (**b**), with their relationship to the normalized arcus tendineus fascia pelvis (ATFP) [turquoise lines extending from the pubic symphysis (P) to the ischial spines (yellow squares), or the pubic symphysis to the ischial spine line (P-IS) for spatial reference. Left-side view of models of one individual with prolapse at rest (**c**) and at maximal Valsalva (**d**). PS and sacrum (S) are shown in the midsagittal plane. Ut uterus, V vagina, CL cardinal ligament, USL_d deep uterosacral ligament. (© DeLancey)

Fig. 3.

Methodology for measuring the length of the line of action and best-fit curve of cardinal and uterosacral ligaments. Identification of origin of insertion line and best-fit curve for the cardinal ligament, back view (a). Red dots indicate landmarks identified for origins and insertions. Dark blue line connects the center of landmarks to establish the line of action. Red curve present the best-fit curve of ligaments on the cross section (red dash on the top model and cyan line in the bottom). L_s length of the straight line of action. L_c length of the curve. Identifying uterosacral ligament line of action and best-fit curve in axial plane (b). Ut uterus, Cx cervix, V vagina, CL cardinal ligament, USL_d deep uterosacral ligament. Modified from [5]. (© DeLancey)

Fig. 4. Straight length and angle of ligaments at rest and maximal Valsalva. Average straight length and angle of cardinal ligament (*CL*) and deep uterosacral ligament (*USL_d*) are shown based on one average, midsagittal image from a healthy woman, with outline for uterus, vagina, pubic symphysis, and sacrum. (© DeLancey)

Fig. 5.

Relationships between cardinal and deep uterosacral ligament curve lengths at rest and at strain in women with normal support and those with prolapse. Statistically significant differences for rest versus strain, and difference (Δ) in ligament-length changes for normal support versus prolapse comparisons: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Other comparisons are discussed in the text.(© DeLancey)

Fig 6.

Relationships between cardinal and deep uterosacral ligament angles with body axis at rest and strain in women with normal support and those with prolapse. Statistically significant differences for rest versus strain comparisons: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. Other comparisons are discussed in the text (© DeLancey)