THE CONTRIBUTION OF PELVIC MUSCLE AND LIGAMENT WEAKNESSES TO THE DEVELOPMENT OF STRESS URINARY INCONTINENCE

by

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Abstract

The symptoms of Stress Urinary Incontinence (SUI) and Pelvic Organ Prolapse (POP) are incited by strenuous activities, such as a valsalva maneuver, cough or lifting heavy objects. SUI is characterized by weakened bladder neck support and urine leakage. POP is characterized by the displacement of pelvic organs into the vaginal space. In women, the symptoms of SUI and POP often coexist, yet their relationship remains ambiguous. The POP-related defects that are relevant to SUI are unknown and are yet to be examined. Damages in pelvic floor muscles and cardinal and uterosacral ligaments are potential defects leading to SUI, since they are commonly found in SUI patients with POP symptoms. These defects can be objectively evaluated using Pelvic Muscle Strength test and Pelvic Organ Prolapse Quantification (POPQ) test. The current study aims to explore the contribution of pelvic muscle and ligament weaknesses to the development of SUI by developing a biomechanical model of a female pelvic support system. The model simulates the behavior of a pelvic system during a valsalva maneuver, and it incorporates muscle strength score and POPQ points. Patient data were collected and implemented into the model to estimate the material parameters that describe the stiffness properties of the vaginal and ligament tissues for clinical patients. Using the model with parameters, the effect of varied degree of muscular and ligament weaknesses on the changes in the bladder neck and apical vaginal supports were assessed for the patients.

The estimated vaginal and ligament parameters were shown to vary, illustrating the diverse material properties of pelvic tissues in individuals. In modeling, simulated conditions of defective muscles and ligaments were demonstrated to contribute to bladder neck and vaginal apex prolapse, consistent with the clinical conditions of POP; alternatively, simulated conditions of restored muscular and ligament supports were shown to help re-establish both bladder neck and vaginal apex supports. The results exhibit the impact of compromise of

pelvic muscles and ligaments on the development of SUI and vaginal apex prolapse and suggest a mechanism of how pelvic muscles and vaginal apex rehabilitation impact SUI and vaginal apex supports in patients with coexisting POP symptoms.

Preface

The thesis entitled "The contribution of pelvic muscle and ligament weakness to the development of Stress Urinary Incontinence" presents the research performed by Clare Yip. The research conducted in this thesis was supervised by Dr. Farrokh Sassani and co-supervised by Dr. Ezra Kwok. In this section, we briefly explain the contents of the papers that will be submitted for publications. We also clarify the relative contributions of co-authors in the papers

- A version of Chapter 2, 3 and 4 will be submitted for publication to present the development and use of a biomechanical model with clinical application to assess the contribution of pelvic musculature weakness to the development of Stress Urinary Incontinence. The authors for this publication will include Clare Yip, Professor F. Sassani, Professor E. Kwok, Doctor R. Jackson, and Professor G. Cundiff. The developed model is described in Chapter 2 of this thesis. The clinical application including clinical patient data collection, parameter estimation and modeling of pelvic floor defects, is explained in Chapter 3 of this thesis. The results explicating the effect of pelvic muscle weakness on the bladder neck and vaginal support are outlined in Chapter 4 of this thesis. The author of this thesis was the principal researcher of this publication. Professor F. Sassani assisted in the formulation of the biomechanical model of the female pelvic floor and participated in the coordination of the study. Professor E. Kwok assisted in the analysis of the data, and participated in the coordination of the study. Doctor R. Jackson participated in identifying the inadequacies of SUI management methods and assisted in the understanding of the female pelvic anatomy. Professor G. Cundiff participated in formulating the current research problem and assisted in the understanding of the female pelvic anatomy. In terms of clinical patient data, approval to use the database previously used for *The*

- A version of Chapter 2, 3 and 5 will be submitted for publication to present the development and use of a biomechanical model with clinical application to assess the the contribution of cardinal and uterosacral ligament weakness to the development of Stress Urinary Incontinence. The authors for this publication will include Clare Yip, Professor E. Kwok, Professor F. Sassani, and Professor G. Cundiff. The developed model is described in Chapter 2 of this thesis. The clinical application including clinical patient data collection, parameter estimation and modeling of pelvic floor defects, is explained in Chapter 3 of this thesis. The results explicating the effect of cardinal and uterosacral ligament weakness on the bladder neck and vaginal support are outlined in Chapter 5 of this thesis. The author of this thesis was the principal researcher of this publication. Professor E. Kwok assisted in the analysis of the data, and participated in the coordination of the study. Professor F. Sassani assisted in the formulation of the biomechanical model of the female pelvic floor and participated in the coordination of the study. Professor G. Cundiff participated in formulating the current research problem and assisted in the understanding of the female pelvic anatomy. In terms of clinical patient data, approval to use the database previously used for *The PESSRI study* was obtained from the UBC Providence Health Care Research Ethics Board. The certificate number of the ethics certificate obtained is H10-00817.

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List of Abbreviations

Symbol	Description
Aa_{rest}	Position of bladder neck (POPQ point *Aa*) at rest, *cm*
Aa_{strain}	Position of bladder neck (POPQ point *Aa*) on strain, *cm*
C_{rest} or D_{rest}	Position of vaginal apex (POPQ point *C* or *D*) at rest, *cm*
C_{strain} or D_{strain}	Position of vaginal apex (POPQ point *C* or *D*) on strain, *cm*
$C1_{PPM}$	Material parameter of pubococcygeus-puborectalis muscle, *N*
$C2_{PPM}$	Material parameter of pubococcygeus-puborectalis muscle
$C1_{AL}$	Material parameter of apical vaginal ligament, *N*
$C2_{AL}$	Material parameter of apical vaginal ligament
$C1_{V}$	Material parameter of vagina, *N*
$C2_{V}$	Material parameter of vagina
$dl_{BN,V}$	Change in bladder neck position due to vaginal elongation, *cm*
F_{1R}, F_{2R}	Forces of iliococcygeus muscles at rest, *N*
F_{1S}, F_{2S}	Forces of iliococcygeus muscles on strain, *N*
F_{3R}	Muscle contractile force at rest, *N*
F_{3S}	Muscle contractile force on strain, *N*
F_4	Bladder weight, *N*
F_5	Force of valsalva, *N*
F_6	Tensile force of vagina, *N*
F_{7S}	Tensile force of cardinal ligament, *N*
F_{8S}	Tensile force of uterosacral ligament, *N*
F_{AS}	Natural abdominal supporting force, *N*
g	Gravitational constant, m/s^2

IAP	Intra-abdominal pressure, N
P_V	Pressure of valsalva, N
I_{PPM}	Percent pelvic muscle impairment (%)
I_{AL}	Percent apical vaginal ligament impairment (%)
$l_{o,PPM}$	Initial length of pubococcygeus-puborectalis muscle, cm
l_{PPM}	Final length of pubococcygeus-puborectalis muscle, cm
l_{IM}	Length of iliococcygeus muscle, cm
$l_{o,CL}$	Initial length of cardinal ligament, cm
l_{CL}	Final length of cardinal ligament, cm
$l_{o,UL}$	Initial length of uterosacral ligament, cm
l_{UL}	Final length of uterosacral ligament, cm
$l_{o,DV}$	Length of unsupported distal vaginal wall, cm
l_w	Width of vagina, cm
V_u	Bladder volume, mL

Greek

Θ_1, Θ_2	Inclination of iliococcygeus muscle, degree
Θ_3	Inclination of pubococcygeus-puborectalis muscle, degree
Θ_5	Inclination of valsalva force, degree
Θ_6	Inclination of vagina, degree
Θ_7	Inclination of cardinal ligament, degree
Θ_8	Inclination of uterosacral ligament, degree
Θ_{AS}	Inclination of natural abdominal supporting force, degree
Θ_S	Angular change of iliococcygeus muscles, degree
ρ_u	Urine density, kg/m^3

Glossary

[1] Stress Urinary Incontinence (SUI) is a pelvic floor disorder characterized by weakened bladder neck support and urine leakage [1].

[2] Pelvic Organ Prolapse (POP) is a pelvic floor disorder characterized by the displacement of pelvic organs into the vaginal space [2, 3].

[3] Mid-urethral tape procedure involves implanting a sling within the anterior part of the vagina to re-support the mid-urethra at times of increases in intra-abdominal pressure [4-6].

[4] Pelvic organ prolapse reconstructive surgeries involve repairing the pelvic floor to re-establish its normal anatomy and function [7-16].

[5] Pelvic floor muscle training (PMT), known as Kegel exercises, is a popular physical therapy that strengthens pelvic floor muscles to prevent or treat mild SUI conditions. PMT was introduced by Arnold Kegel more than 50 years ago [17, 18]. PMT consists of two parts: strength training and timing skill. The aim of the exercise is to develop strength and cross-sectional area of the levator ani muscle so as to enhance support to the urethra. The protocol of the PMT involves scheduling a time to exercise, gradually increasing the intensity of the exercise and enhancing the structural change in the muscles.

[6] Intra-abdominal pressure (IAP) is a steady-state pressure within the pelvic-abdominal cavity [19, 20]. It is generated by the muscles of the abdomino-pelvic cavity, which consists of the pelvic floor muscles, the abdominal muscles and the diaphragm. Involuntary coughing and maximal valsalva are two activities that can generate additional IAP inside the

abdominal cavity, and these activities are often used during clinical exams and imaging to assess the type and severity of female pelvic disorders for individual patients [21-26].

[7] Coughing can generate an increase of 50 to 195 mmHg in IAP [21, 25]. During a maximal cough, the diaphragm, the abdominal muscles (ie. mainly the transverse abdominus and the obturator internus), and the pelvic floor muscles (ie. mainly the pubococcygeus muscles) are strongly activated in asymptomatic and nulliparous women [24, 25].

[8] Valsalva Maneuver can generate an increase of 45 to 113 mmHg in IAP [21]. During a maximal Valsalva, the diaphragm, all the abdominal and pelvic floor muscles as well as the chest wall muscles (intercostal muscles) are activated in asymptomatic and nulliparous women [24, 26].

[9] Bladder is a hollow, extensible organ. It is situated in the anterior half of the pelvic cavity and is bounded anteriorly by the pubic symphysis and laterally by the pelvic wall. The caudal end of the bladder contains an opening that is continuous with the urethra to allow urine to pass through. The bladder base lies on the superior portion of the anterior vaginal wall and is connected to it by connective tissues [27]. The bladder wall consists of smooth detrusor muscles [28, 28]. It functions to store and expel urine [29]. It contracts during both filling and voiding of urine to generate intravesical pressure. During filling, the bladder generates a low pressure of 10 to 15 cmH2O with little or no contraction [30]. During voiding, the bladder contracts to generate a pressure that exceeds the urethral closure pressure to allow urine flow to the urethra.

[10] Urethra is a muscular tube that extends from the caudal opening of the bladder to the external orifice. It is divided into the bladder neck, the striated muscular urethra, and the distal urethra [30-32]. It allows urine expulsion, as well as prevents urine leakage during normal bladder filling and at times of sudden increases in intravesical pressure. To allow urine expulsion, the urethral wall relaxes. To help prevent leakage, the urethra generates urethral closure pressure.

[11] The bladder neck, also known as the urethrovesical junction or urethral-bladder junction, contains the internal sphincter. It is made up of both detrusor muscles bundles and smooth muscles. It surrounds the proximal urethra to help close the urethral lumen [33].

[12] The striated muscular urethra contains the external sphincter (striated urogenital sphincter) and the striated muscles of the urogenital diaphragm [33].

[13] The striated urogenital sphincter, also known as the external sphincter, consists of an inner circular smooth muscle layer and an outer circular striated muscle layer [33]. It is composed of type I (slow twitch or passive) fibers and type II (fast twitch or active) fibers. It helps to generate urethral closure pressure during at rest and under acute stress [34].

[14] The urogenital diaphragm is made up of compressor urethrae and urethrovaginalis muscles. These muscle fibers help to compress the urethral lumen [33].

[15] Pelvic floor organs, including the vagina, urethra, bladder, uterus, and rectum, are enclosed inside the pelvic bone and are stabilized by the pelvic floor structures.

[16] Pelvic floor is a physiological complex system comprised of interconnected contractile muscles and supporting connective tissues that act in concert to maintain continence in normal healthy individuals [20, 35]. The pelvic floor supportive structures are classified into Level I, II and III vaginal supportive structures.

[17] Pelvic bones include pubic bone (symphysis), ilium, ischial spine, sacrum and coccyx.

[18] Vagina is a hollow, muscular tube that extends from the cervix to the external orifice [20]. In a sagittal view, the superior portion of the vagina is directed toward the last third and fourth bone of the coccyx. This portion lies on the rectum, which in turn is supported by the iliococcygeus muscle. The distal anterior portion of vagina fuses with the lower two-thirds of the urethra, and it is also connected to the pubococcygeus-puborectalis muscle band [18].

Vagina has four layers, the epithelium, subepithelium, muscularis and the adventitia [20, 36]. The functions of vagina are described in 18a.

[18a] Vagina aids in supporting the pelvic organs. The anterior vaginal wall (V) supports the bladder and the urethra anteriorly. The upper portion of the vagina, through its attachments to the cardinal ligaments and uterosacral ligaments, support the uterus and cervix apically, and the posterior wall of the vagina supports the rectum posteriorly. In terms of continence, the vagina forms part of the supportive layer on which the bladder neck rest. At rest, vagina is being compressed against the pubic bone by the resting tone of the pelvic floor muscles in a cephalad direction. At times of increases in IAP, the vagina is being compressed and pulled against the pubic bone by the active tone of the pelvic floor muscles in a cephalad direction [33]. The closing and pulling action of the muscles stabilize the vagina so the bladder neck can be compressed against a firm supportive layer, so as to increase the urethral closure pressure [25, 33, 37-40].

[19] Vaginal epithelium forms the superficial layer of the vagina, and it is composed of squamous cells [20, 36].

[20] Vaginal subepithelium lies beneath the epithelium and is a thick, dense collagen layer that provides passive strength to the vagina.

[21] Vaginal muscularis consist of smooth muscle bundles with smaller amount of collagen, elastin, and vascular tissue. It provides active longitudinal and central support to the vagina [20].

[22] Adventitia is an extension of the endopelvic fascia (loose connective tissue) that surrounds the vagina and the adjacent pelvic organs to allow for their independent expansion and contraction [20, 36].

[23] Cardinal ligaments arise from the cervix and the upper vagina and insert in the sacrum. They are composed of parallel-oriented collagen fibers and elastin. They provide Level I

vaginal support by suspending the upper vagina and the uterus [20]. In standing position, the ligaments maintain the upper vaginal axis nearly horizontal so that the vagina can be supported by the pelvic floor muscles. During straining conditions, cardinal ligaments provide passive resistance against the load.

[24] Uterosacral ligaments arise from the cervix and the upper vagina and insert in the sacrum near the area of sacrospinous ligaments. They are composed of parallel-oriented collagen fibers and elastin. They provide Level I vaginal support by suspending the upper vagina and the uterus [20]. In standing position, the ligaments maintain the upper vaginal axis nearly horizontal so that the vagina can be supported by the pelvic floor muscles. During straining conditions, uterosacral ligaments provide passive resistance against the load.

[25] Pubocervical fascia is a loose connective sheet of tissue that lies beneath the bladder as well as on top of the rectum. Its sides are lined by a pair of arcus tendineus fascia pelvis [36]. It provides Level II vaginal support, since it suspends the mid-portion of both the anterior and the posterior vaginal wall [20]. Anteriorly, this support helps to prevent herniation of the bladder and urethra onto the vagina. Posteriorly, it helps to prevent herniation of the rectum onto the vagina [35].

[26] Arcus tendineus fascia pelvis (ATFPs) is a fascial thickening that originates from the ischial spine and inserts into the pubic symphysis. The proximal parts of the ATFPs line the sides of pubocervical fascia to help suspend the pubocervical fascia [39].

[27] Pelvic floor muscles, also known as levator ani muscles, play a major role in supporting the pelvic organs and in urinary and defecatory functions [20]. The muscles are made up of parallel-oriented skeletal muscle fibers, and they are composed of pubococcygeus, puborectalis and iliococcygeus muscles. Together with the perineal membrane, they provide Level III vaginal support. At rest, the muscles provide a resting tone, and under acute stress, they actively contract. The contractile activity compresses the vagina, urethra, rectum and the pelvic floor against the pubic bone in a cephalic direction to narrow the urogenital hiatus [21,

33, 39, 41]. Levator ani muscles also forms the inferior boundary of the abdomino-pelvic cavity, and they help to generate additional IAP during strenuous activities.

[28] Pubococcygeus muscles are part of the pelvic floor muscles that originate on the posterior surface of the pubic symphysis. They fuse with the vagina and the urethra, connect to the distal end of the iliococcygeus muscles and inserts on the anococcygeal raphé near the coccyx. Together with the puborectalis, the normal tone of these muscles narrows the urogenital hiatus by pulling the vagina, urethra, perineum and rectum anteriorly toward the pubic bone [21, 33, 39, 41]. The muscle tone stabilizes the vagina and enhances the bladder neck support. The pubic ends of the pubococcygeus muscles are also attached to the pubocervical fascia and the ATFPs. Contraction of these muscles helps ATFPs to hold up the pubocervical fascia to enhance Level II vaginal support [20].

[29] Puborectalis muscles are part of the pelvic floor muscles that originate from the posterior surface of the pubic bone. They form a sling around the mid-urethra, vagina, rectum and perineum. Together with the pubococcygeus, the normal tone of these muscles narrows the urogenital hiatus by pulling the vagina, urethra, perineum and rectum anteriorly toward the pubic bone [21, 33, 39, 41]. The muscle tone stabilizes the vagina and enhances the bladder neck support. The pubic ends of the puborectalis muscles are also attached to the pubocervical fascia and the ATFPs. Contraction of these muscles helps ATFPs to hold up the pubocervical fascia to enhance Level II vaginal support [20].

[30] Iliococcygeus muscles are pelvic floor muscles that extend from the arcus tendineus levator ani and insert to the anococcygeal raphé near the coccyx (Bo et al., 1997). These muscles form a horizontal plate that spans from one pelvic sidewall to the other. It serves as a supportive diaphragm behind the pelvic organs [20, 33].

[31] Urogenital hiatus is the space between the pelvic floor muscles through which the urethra, vagina and rectum pass [20].

[32] Perineum is the area of the pelvic outlet inferior to the pelvic floor. It is bordered by the ischial tuberosities, sacrotuberous ligaments and coccyx. The perineum is divided into the urogenital triangle anteriorly and the anal triangle posteriorly, with the perineal body situated in between [20].

[33] Perineal membrane is a thick fibrous tissue that spans the urogenital triangle. It attaches laterally to the left and right pubic arches and connects posteriorly to the perineal body. Both urethra and vagina perforates through the perineal membrane at the urogenital hiatus. With resting tone, the perineal membrane fixes the distal urethra, distal vagina and perineal body to the left and right pubic arches [20].

[34] Perineal body is the area in between the vagina and the anus. It is also the point at which the superficial and deep perineal muscles, perineal membrane, external anal sphincter, and pelvic floor muscles unite together. The perineal body helps to support the distal vagina and maintain normal anorectal function [20].

[35] Urogenital triangle contains the urethral and vaginal opening [20].

[36] Anal triangle contains the anus [20].

[37] Pressure transmission ratio characterizes the urethral closure mechanism dynamics during intravesical pressure increases caused by strenuous activities [33].

[38] A maximal cough is used in clinical tests and imaging studies to mimic the real situation of a hard cough.

[39] Valsalva maneuver is used in clinical tests and imaging studies to mimic the rapid generation and application of additional IAP during strenuous activities.

[40] Stiffness is the ratio of the applied abdominal pressure increase in a given pelvic floor displacement (cmH_2O/mm) [21].

[41] Digital pelvic floor muscle strength test evaluates the pelvic muscle contraction strength in women. The test was initially developed for older women (55 to 90 years) with urinary incontinence. The subject is tested in supine, sitting and or standing position, and is asked to maximally squeeze her perivaginal muscles around one or two of the examiner's fingers. The muscle strength is then evaluated based on a 5-point Oxford grading scale. For a younger population of women, a newer test based on a 9-point Oxford grading scale was later introduced [42]. This test evaluates the pelvic muscle contraction strength in three aspects (ie. pressure, displacement and duration), and it is commonly used in pelvic floor studies [24, 26, 43-45].

[42] Vaginal squeeze pressure test evaluates the pelvic muscle contraction strength in women, and it involves inserting a pressure probe into the vagina of the subject. The centre portion of the probe is located about 3.5 cm from the vaginal introitus. The subject is then asked to perform a maximal pelvic floor muscle contraction and then an endurance contraction at which she draws in and lift the muscle, holding the contraction for as long as possible to a maximum of 30 seconds. Vaginal squeeze pressure test is commonly used in pelvic floor studies [21, 26, 45, 46].

[43] Motor unit potential duration is a sensitive indicator of nerve damage. It is a measure of the duration the motor units takes to activate during a voluntary contraction [47].

[44] Pudendal nerve terminal motor latency is a measure of the time it takes the pelvic floor muscle to contract the external anal sphincter after stimulation of the pudendal nerve [48].

[45] Resilience is a measure of the work (in joules) needed to extend the specimen to a specific length [49].

[46] Behavioral therapy involves diet counselling. Patients will be advised to maintain regular bowel habits, promote weight loss, modify certain diet habits, specifically fluid intakes, and advise to avoid movements such as jumping or running [50, 51].

[47] Stress cough test involves filling a patient's bladder to its maximum normal capacity (ie. 400 to 600 ml). The patient is then asked to cough and perform a Valsalva maneuver in supine and upright position. A patient is said to have a negative stress cough test or no SUI when there is no urine leakage during coughing and on Valsalva. A patient is said to have SUI when there is urine leakage [50, 51].

[48] 48-hour pad test requires the patient to wear a pad for 48 hours. The weight of the pad is then measured after 48 hours. Weight of urine greater than 15 grams indicates abnormal urine loss. A negative pad test means that there is less than 10 gram of leaked urine in 24 hours [52] .

[49] Medical history session involves gathering, from individual patients, their gynaecological and obstetrical records, such as previous pregnancy, childbirth and pelvic surgeries, social facts (ie. types of work), physical habits (ie. smoking, intake of caffeine), and coexisting diseases, including diabetes, stroke, neurological disease, and pulmonary diseases etc. [50, 51].

[50] Questionnaires are given to and filled in by patients who have pelvic floor disorders. The information is used to evaluate the type and severity of urinary incontinence, pelvic floor symptoms (ie. vaginal bulge), and the impact of incontinence and or pelvic organ prolapse on the patient's quality of life [50, 53]. The most common questionnaires include The Incontinence Quality-of-Life Questionnaire (I-QOL) and The Pelvic Floor Dysfunction Questionnaire.

[51] Quality-of-Life index is a score that is used to evaluate the impact of urinary incontinence on individual patients. It is a summation of scores based on the responses of the Incontinence Quality-of-Life Questionnaire (I-QOL), filled in by individual patients [54].

[52] The Incontinence Quality-of-Life Questionnaire (I-QOL) is a 22-item questionnaire designed to assess the quality of life of patients with urinary incontinence. The impact of

incontinence on the quality of life is based on total score, known as quality-of-life index. I-QOL has been commonly used as an outcome measure in the clinical trials of SUI treatments [54-56].

[53] The Pelvic Floor Dysfunction Questionnaire is designed to evaluate the impact of the pelvic floor dysfunction symptoms have on the patients' daily lives. The Pelvic Floor Dysfunction Questionnaire is divided into 8 areas, each with questions related to specific types of dysfunction. These areas include urinary incontinence, urinary irritative symptoms, voiding dysfunction, pelvic organ prolapse symptoms, fecal incontinence, defecatory dysfunction, pelvic pain, and sexual dysfunction. Likert scale assignment was used to respectively quantify severity (none, 0; minimally, 1; moderately, 2; severely, 3) and duration of symptoms (never, 0; <25% of time, 1; <50% of time, 2; <75% of time, 3; 100% of time, 4) and impact on quality of life [57].

[54] The Q-tip test evaluates urethral mobility, and it involves placing a small Q-tip in the urethra at the bladder neck [50, 58]. The patient is asked to perform a maximal Valsalva, and he change in the angle of the urethra is determined. An angular change of greater than 30 degrees from rest to maximal straining often means there is significant weakness in the mid-urethral support [35].

[55] Urodynamic test assesses the behavior of the bladder during urine storage and urination. It is the "gold standard" diagnostic procedure for identifying SUI symptoms and evaluating its severity. During the test, the bladder is filled to maximum normal capacity (ie. 400 to 600 ml). The patient is asked to cough and perform Valsalva maneuver in supine and upright position. A patient is said to have SUI when there is urine leakage during coughing and under Valsalva. The severity of SUI is based on the amount of leakage volume [59, 60]. A patient is said to have no SUI when there is no urine leakage during coughing and under Valsalva. Variables including bladder capacity, intravesical or bladder pressure, abdominal pressure, leak-point pressure are also measured during the test and recorded in a cystometrogram. The difference between the intravesical pressure and abdominal pressure describes the pressure and the contraction of the detrusor muscles (muscles of the bladder).

[56] Severity of urinary incontinence is based on the amount of leakage volume. The patients with mild urinary incontinence will have mean volume of urine loss of less than 1 ml; patients with mild to moderate urinary incontinence have mean volume of urine loss between 1 ml to 8 ml; patients with severe urinary incontinence have mean volume of urine loss of greater than 8 ml [59, 60].

[57] Imaging techniques include ultrasound and Magnetic Resonance Imaging (MRI). Ultrasound yields dynamic real-time anatomical changes of pelvic structures. Magnetic resonance imaging (MRI) yields both static and dynamic anatomical images of pelvic organs and structures. MRI can yield accurate images of soft-tissue due to the high soft-tissue contrast and multiplanar acquisition. Valsalva maneuver (straining) and pelvic floor contraction are commonly used during imaging to assess the severity of SUI and pelvic prolapse symptoms [61, 62].

[58] POPQ is a universally accepted system for quantifying pelvic organ prolapse [63]. It was drafted by International Continence Society (ICS), American Urogynecologic Society (AUS), and the Society of Gynecologic Surgeons (SGS) in 1993, and the system was finally adopted in 1996. It describes the anatomic position of pelvic organs and the extent of the prolapse. POPQ measurements are taken when the subject is performing a maximal Valsalva and has developed full extent of the prolapse.

[59] POPQ measurements include 3 lengths and 6 defined points [63]. The plane of hymen is the reference point for all measurements and is defined as zero. The measurements are in centimetres. Points that are found above or proximal to the hymen are recorded as negative number, while points that are found below or distal to the hymen are recorded as positive number. In general, the normal POPQ points are as follows: (-3, -3, -7, -9, -3, -3, 9, 2, 2) for points *Aa*, *Ba*, *C*, *D*, *Bp*, *Ap*, *tvl*, *gh*, *pb*).

[60] Full extent of the prolapse is developed when the patient strain in standing position, and the subject has confirmed that the size of the prolapse seen and the extent of protrusion are the most extensive and severe [63].

[61] Point *C* and *D* are the superior points that define the most proximal locations of the apical vagina, and they are most relevant to uterine prolapse [63].

[62] Point *Aa* and *Ba* are the anterior points that define the anterior support of the mid-vaginal wall, and they are most relevant to cystocele (bladder prolapse) [63]. Point *Aa* reflects the position of the bladder neck junction. Point *Ba* indicates the most distal or dependent position of upper anterior vaginal wall from vaginal fornix to point *Aa*.

[63] Point *Ap* and *Bp* are the posterior points that define the posterior support of the mid-vaginal wall, and they are most relevant to rectocele (prolapse of the rectum) [63].

[64] Hyperelasticity, also known as non-linear elasticity, is demonstrated in soft tissues. Under uniaxial tension, parallel-fibered soft tissues exhibit an initial low modulus (ie. slope of stress-strain curve) region, an intermediate region of gradually increasing modulus, a region of maximum and relatively constant modulus, and a final region of decreasing modulus before complete tissue rupture happens [64]. The low modulus region is due to the straightening of the collagen fibers of the tissues. This is the most relevant region because it corresponds to the physiological range in which the tissue normally functions.

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Dedication

I would like to dedicate this work to my dearest grandfather. I thank him for supporting all the decisions I have made throughout these years and encouraging me to be persistent in achieving my goals. May his beautiful soul rests in peace.

Chapter 1

Introduction

Stress Urinary Incontinence (SUI) is a pelvic floor disorder that involves involuntary urine leakage during strenuous activities, such as coughing, sneezing, laughing, lifting heavy objects or performing a valsalva maneuver [1]. In Canada, as many as 3.3 million people suffer from some form of incontinence, and approximately 50% of the affected women suffer from SUI[1] [65-67]. According to the Canadian Continence Foundation, the total direct costs spent on UI supplies (i.e. pads) and nursing care is $1 billion per year, and the total indirect cost (i.e. loss of productivity, absenteeism and individual, familial, and social impacts) is estimated to be $2.6 billion per year. The increasing incidences of SUI in women and economic burden to the women, their employers and to the health care system show that SUI is a significant problem that needs immediate attention.

Pregnancy and childbirth are well-known etiologic factors leading to SUI [68-70]. About 16% (sample size = 120) to 20% (sample size = 241) of pregnant women experienced SUI; 10.3% (sample size = 484) to 50% (sample size = 241) of women experienced SUI after childbirth [71-73]. Until now, the association between pregnancy, childbirth and SUI remained unclear due to its complexity. The complexity is related to the degree and the type of damage during pregnancy and childbirth to the pelvic floor, a system comprised of interconnected contractile muscles and connective tissues that normally act together to maintain continence in healthy individuals [20, 35]. For

[1] Stress Urinary Incontinence, while it is more prevalent in women, may sometimes occur in men who have had prostate surgery.

example, pelvic floor muscles can become overstretched and damaged mechanically and nervously; at the same time or separately, connective tissues can be overly stretched and torn as well [74-79]. These damages can impair the support of the bladder neck that is crucial to the maintenance of urinary continence.

Pelvic Organ Prolapse (POP) is a pelvic floor disorder that often coexists in females with SUI symptoms. POP is characterized by the displacement of pelvic organs from their normal positions into the vaginal space [2, 3]. POP not only shares the same etiological factors as SUI, but its symptoms are also incited during strenuous activities. About 40 to 63% of females with SUI were demonstrated to have coexisting POP symptoms [80-83]. Despite the high coexisting rate, the relationship between SUI and POP remains ambiguous, and their common pelvic causes are yet to be examined.

There are many ways that SUI can develop; thus, selecting the best treatment option is very patient-specific. Some mild cases can be fixed without surgery, but for severe SUI, identifying the site-specific pelvic anatomical defects is important for selecting a surgical procedure that will successfully correct the problem. Current pelvic treatment methods, mainly the tape procedures, pelvic organ prolapse reconstructive surgeries and pelvic floor exercises, provide unsatisfactory long-term cure rates for SUI patients with coexisting POP symptoms. Also, the available SUI diagnostic methods are inadequate as they provide little information about the pelvic causes of SUI, and they are associated with very low levels of accuracy. To improve the diagnostic accuracy and treatment success of SUI, it is crucial to identify and correct the pelvic defects that cause SUI. Much research has been conducted to identify a technique that is useful in investigating the pelvic defects related to the development of SUI. Biomechanical modeling is found to be useful because it describes the forces and deformations of bodies under a load. Modeling the behaviors of the impaired pelvic floor structures under a load (i.e. cough or valsalva maneuver) can improve our understanding on the association between the pelvic floor defects and SUI.

1.1 Normal Urinary Functions and Pelvic Floor Anatomy

Normal urinary functions and pelvic floor anatomy are crucial to the maintenance of urinary continence. During strenuous activities, there is an increase of intra-abdominal pressure (IAP) inside the pelvic-abdominal cavity. The added pressure exerts expulsive forces on the bladder and the stored urine, which can cause the urethra to open [19, 20]. Functional urinary sphincters and vaginal supportive structures inside the pelvis can effectively resist these expulsive forces and maintain urethral closure [19, 20, 33]. The following sections outline the importance of urinary sphincteric mechanism and vaginal supportive structures to urinary continence.

1.1.1 Urinary sphincteric mechanism

The urinary organs that are relevant to urinary continence include the bladder and the urethra. Bladder is a hollow, extensible organ responsible for storing and expelling urine [29]. Urethra is a muscular tube that is continuous with the caudal portion of the bladder. It contains sphincteric elements that can relax to allow urine expulsion and constrict to prevent urine leakage [30-32].

During filling, the bladder wall contracts and generates an intravesical pressure within the bladder. At the same time, the urethra generates a resting urethral pressure to resist the intravesical pressure. The difference between the intravesical pressure and the urethral pressure is known as the urethral closure pressure. When the urethral pressure is higher than the intravesical pressure, the urethral closure pressure is positive. This positive urethral closure pressure allows urine to be retained in the bladder. During strenuous activities, intravesical pressure can increase to a maximum of 200 cmH_2O [33]. A normal urethra must generate a urethral pressure that exceeds this intravesical pressure to maintain continence [84, 85]. The urethral pressure is mainly contributed by the urethral muscular sphincters, as well as the pelvic floor muscles. At rest, these structures provide constant muscular tone to retain urine in the bladder [86]. During strenuous activities, these structures actively contract to provide a sudden closure mechanism to prevent urine leakage [31, 85].

However, the urethral sphincters can have permanent structural and or nervous failure. These damages cannot be restored, and they can promote urinary incontinence during strenuous activities.

1.1.2 Vaginal wall supportive structures

Anatomically, the pelvic organs and pelvic floor structures are enclosed within the bony pelvis (Figure 1 and 2). The pelvic bones, as shown in Figure 3, provide a rigid base to which all the pelvic organs are anchored and connected via the pelvic floor structures [20].

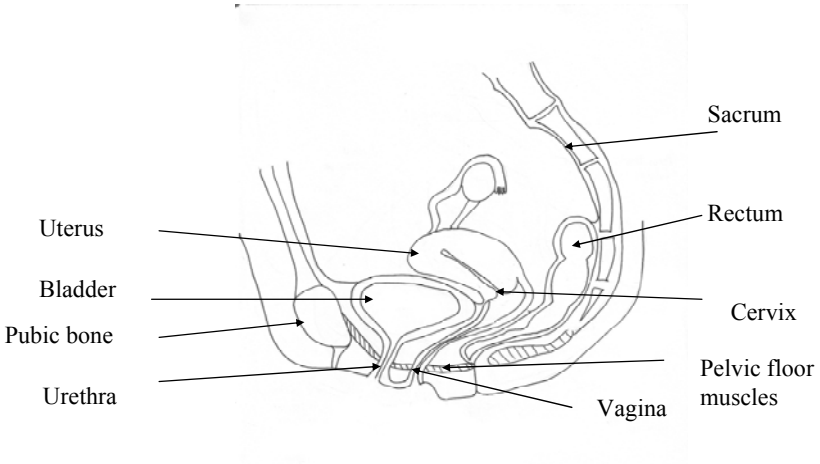

Figure 1 The sagittal view of pelvic organs (vagina, urethra, bladder, uterus, rectum) inside female pelvis.

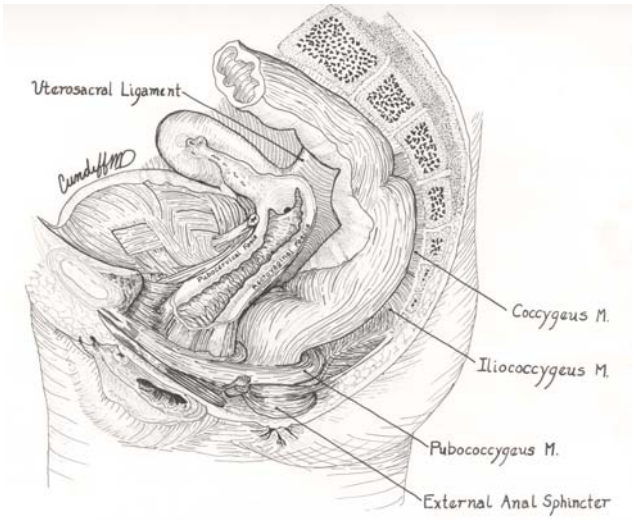

Figure 2 The sagittal view of pelvic floor supportive structures inside female pelvis (figure used with permission from Dr. Geoffrey Cundiff).

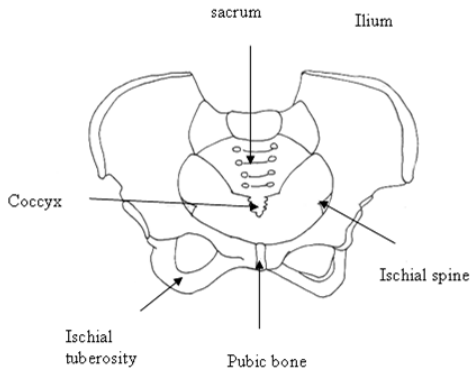

Figure 3 The anterior view of female pelvic bone.

Inside the pelvis, the pelvic organs, including the bladder, urethra, uterus, cervix and rectum, are supported by the vaginal wall. The anterior vaginal wall supports the bladder and the urethra anteriorly. The upper portion of the vagina, through its attachments to the cardinal ligaments and uterosacral ligaments, support the uterus and the cervix apically, and the posterior wall of the vagina supports the rectum posteriorly (Figure 1). The entire vaginal wall is in turn stabilized by other pelvic floor supportive structures as shown in Figure 2. The vaginal wall is supported distally by the pelvic floor muscles (pubocccygeus, puborectalis and iliococcygeus muscles) and the perineal membrane (Figure 4). Laterally, the anterior vaginal wall attaches to the pubocervical fascia and arcus tendineus fasciae pelvis, and apically to the cardinal and uterosacral ligaments [20].

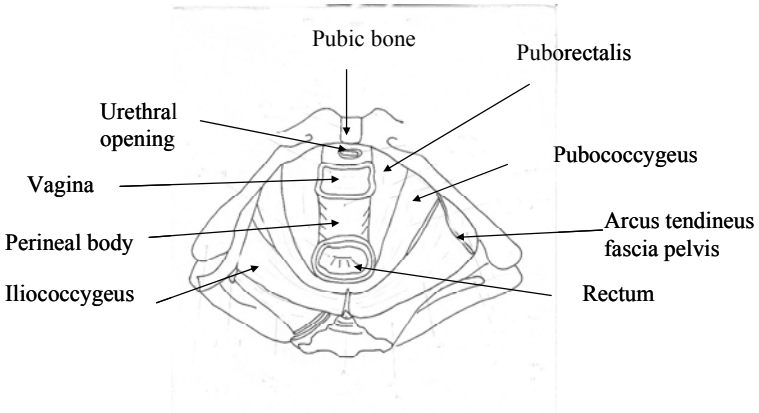

Figure 4 Pelvic supportive structures including the pelvic floor muscles and the perineal membrane that provide distal vaginal support (inferior view of a female pelvis).

During increases in IAP, a well-supported vaginal layer provides a firm backstop against which the urethra, especially the bladder neck region, is compressed [25, 33, 37-39]. Properly supported vagina also allows the increased IAP to be transmitted equally to the bladder and the urethra. This dynamic process called "pressure transmission" causes a simultaneous increase in urethral pressure to enhance urethral closure and maintain urinary continence. For continent women, the pressure transmission ratio is close to 100% [33, 87].

However, the vaginal supportive structures can have structural failure that can impair the vaginal wall support, leading to pelvic organ prolapse. When the pelvic organ, namely the urethra, is not supported adequately, Stress Urinary Incontinence can result. Stress Urinary Incontinence is a pelvic floor disorder that involves weakened bladder neck support and urine leakage during strenuous activities. Unlike the urethral sphincteric damage, the impaired vaginal supportive structures can be restored. The current research focuses on the importance of rehabilitating the vaginal supportive structures to urinary continence.

1.1.2.1 Pelvic floor muscles and apical vaginal ligaments

Pelvic floor muscles and apical vaginal ligaments are among the most important pelvic floor structures that provide vaginal wall support. The current research will focus on their roles in urinary continence, since evidence of damages in these structures have been commonly found in incontinent women [11, 14, 15, 21, 46, 74, 79, 88].

Pelvic floor muscles are composed of pubococcygeus, puborectalis and iliococcygeus muscles. During at rest condition, the iliococcygeus muscles normally provide a resting tone to support the pelvic organs. The pubococcygeus-puborectalis muscle band (pubovisceral muscles), on the other hand, functions as a tensor of the distal vaginal wall to support the bladder and the urethra [20, 89]. During rises of IAP, pelvic floor muscles actively contract to minimize the pressure acting on the pelvic connective tissues and organs. To maintain continence, the pubococcygeus-puborectalis muscle band (pubovisceral muscles) pulls the vagina and bladder neck toward the pubic bone to reinforce the striated structures of the urethra [33, 39, 40]. Several ultrasonographic studies have shown that the contractions of pelvic floor muscles help to narrow the urogenital hiatus, stabilize the bladder neck and increase urethral closure pressure. All studied participants performed coughing and Valsalva maneuver to mimic the dynamic pelvic conditions during strenuous activities. In these studies, the diameter of the hiatus, bladder neck descent, and bladder neck mobility were all found to decrease significantly when the pelvic floor muscles are co-activated during straining. The stiffness of the

urethral supportive layer and urethral closure pressure, on the other hand, were found to increase significantly when the pelvic floor muscles are contracted [21, 38, 41]. The level of significance (*P*) used in these studies is 0.05.

In terms of apical vaginal ligaments, both cardinal and uterosacral ligaments function to suspend the upper vagina and the uterus [20]. The integrity of these ligaments has recently been observed in clinical studies to be related to urinary functions. In these studies, women with weakened apical vaginal support were found to have co-existing leakage symptom, and digital support of the upper vagina eliminated leakage symptom in 90-94% of these women (sample size = 20 to 90) [90, 91]. The exact role of these ligaments in continence is still unclear. However, existing literature suggested that they provide resistance to allow pelvic floor muscles to contract sufficiently so as to tense the vaginal supportive layer. A firm vaginal layer can stabilize the bladder neck to prevent premature activation of the bladder base's stretch receptors that may otherwise stimulate urine flow [92, 93] .

1.2 Anatomical Pelvic Defects Associated with Stress Urinary Incontinence

Up to this date, the understanding of the causation of SUI is still in its infancy, and no single cause has been determined to explain its occurrence. Women with SUI usually have pressure transmission ratio less than 100% [33, 87], and the reasons for that still need to be investigated. Defects in the vaginal support system may contribute to this decreased pressure transmission ratio, since women experiencing SUI symptoms were found to have coexisting defects in this support system. These defects are related to Pelvic Organ Prolapse (POP), and they bring about anatomical and functional changes of the pelvic floor [20, 39]. The most common pelvic defects found in women who experienced SUI symptoms during pregnancy and after childbirth included pelvic floor muscle weakness, apical vaginal ligament attenuation, and bladder neck mobility. These defects are potential pelvic causal factors of SUI, and they will be examined in the current study.

Pelvic floor muscle weakness compromises distal vaginal support, and it is characterized by reduced pelvic muscle contraction strength [20, 33]. Digital muscle strength test and vaginal squeeze pressure test are commonly used to evaluate the pelvic muscle contraction strength in women. In the pelvic studies performed by Howard *et al*. (2000) and Morved *et al*. (2004), women who had SUI after childbirth demonstrate significantly lower pelvic muscle contraction strength ($P < 0.010$) compared to those of the nulliparous women (n = 35 to 103) [21, 46]. Pelvic muscle weakness can be due to neurological and mechanical damage of the pelvic floor muscles. Neurological muscle damage is evaluated by two common measures taken during the electromyographic studies: motor unit potential duration (MUPD) and pudendal nerve terminal motor latency (PNTML). Women after childbirth have been shown to have significant increase in these two measures [47, 48]. Mechanical muscle damage, on the other hand, involves muscle attenuation and discontinuity or loss of muscle fibers. This type of muscle damage has been demonstrated in parous women with SUI symptoms using Magnetic Resonance Imaging (MRI) techniques [74, 79]. According to the MRI study by DeLancey *et al*. (2003), damage in the pubococcygeus-puborectalis muscles (pubovisceral muscles) have shown to be most relevant to SUI, since 91% of the pelvic muscle damage found in women with SUI symptoms occur in these pelvic muscles (sample size = 32). According to the MRI study by Tunn *et al*. (2006), 76% of the women with SUI (sample size = 54) demonstrated discontinuity or loss of pelvic muscle fibers. In both imaging studies, childbirth was evidently shown to bring about pelvic trauma and incontinence problems, since mechanical muscle damages were only found in women with previous childbirth and over 71% of these parous women have coexisting SUI symptoms.

Cardinal and uterosacral ligament attenuation compromises apical vaginal support, and it is characterized by the prolapse of uterus and or vaginal apex[94]. In the study by Reay *et al*. (2003), mechanical tests were performed on the apical vaginal ligaments of women with and without symptomatic apical vaginal prolapse. The study demonstrated a significant reduction in the ligament resilience measures (in joules) in women with symptomatic apical vaginal prolapse compared to those in normal women (sample size = 85, $P = 0.020$). Reduction in the resilience measures were also found to be

correlated with increasing age (correlation coefficient = -0.38 (-0.55 to -0.17)) [49]. The weakening of the apical vaginal support caused by attenuated apical vaginal ligament tissues has been shown to be relevant to the development of SUI. In a Magnetic Resonance Imaging (MRI) study by Summers *et al*. (2006), women with apical vaginal ligament weakness were found to have weakened bladder and urethral support. The loss of apical vaginal support has been shown to have a significant correlation with the degree of failure in the anterior vaginal wall support (r = 0.73, $P < 0.0001$, sample size = 133) [22].

Bladder neck mobility is characterized by the depression of the bladder neck in a caudal direction during straining. Q-tip test and ultrasound are commonly used to assess bladder neck mobility. Women who had SUI after childbirth were found to have significantly higher bladder neck mobility ($P < 0.001$) during straining when compared to that of the healthy nulliparous women [21, 33]. Increased bladder neck mobility indicated impairments in the urethral support system. Results in recent mechanical and imaging studies suggested that pelvic floor muscle and apical vaginal ligament weaknesses are potential defects contributing to bladder neck mobility; nevertheless, the exact mechanisms of how these defects can lead to bladder neck prolapse are still unknown and needs to be examined.

1.3 Current SUI Management Methods

The current SUI management methods mainly focus on correcting the symptoms of urinary incontinence, and they often fail to accurately restore the anatomical pelvic defects that are relevant to the development of SUI for individual patients.

For mild cases of SUI, the management methods involve the use of diaper, behavioural therapy, and pelvic floor exercises. For patients with severe SUI and POP symptoms, surgical treatments, mainly the mid-urethral tape procedure and concomitant pelvic organ prolapse reconstructive surgeries, are recommended. These combined surgical treatments aim to improve both urethral and vaginal support. They offer short-term (1 to 3 years) cure rates of 90% to 96%, but long-term cure rates (> 3 years) of only 70% to 79% (sample size = 32 to 125) in treating the leakage symptoms in patients with

coexisting POP symptoms [7-9, 11-13, 13, 14]. The cure rates were evaluated based on the results of stress cough test, pad test and quality-of-life index. Pelvic floor exercises, on the other hand, provide cures rates of only about 23% to 60% (sample size = 44 to 52) in treating the symptoms of incontinence [95, 96]. The cure rates were evaluated based on the results of pad test, daily leakage episodes, and quality-of-life index.

Currently, none of the available pelvic management methods accurately correct the pelvic causes of SUI. To help improve treatment effectiveness for SUI patients with coexisting POP symptoms, it is essential to identify and correct the site-specific pelvic anatomical defects that cause SUI in these patients.

1.4 Current SUI Diagnostic Methods

The available SUI diagnostic methods mainly focus on the diagnosis of the symptoms of urinary incontinence, and they are inadequate in examining the anatomical pelvic defects that are relevant to the development of SUI for individual patients.

The primary diagnostic tools that are currently available for identifying the type and the severity of urinary incontinence include medical history, questionnaires, Q-tip test, 48-hour pad test, urodynamics, and imaging techniques (ultrasound and MRI). Q-tip test is the most popular clinical exam used for evaluating urethral support, while urodynamics and questionnaires are commonly used to assess the severity of SUI and its impact on the patients' quality of life. Despite their availability, these tests provide little information about the anatomical pelvic causes of SUI. Imaging techniques are useful for identifying the potential pelvic defects that lead to incontinence symptoms in individual women, but they are expensive and are often not accessible clinically.

Currently, none of the available SUI diagnostic methods can accurately identify and evaluate the pelvic causes of SUI for individual patients. To help improve SUI-diagnostic effectiveness and to allow health practitioners to prescribe more targeted treatments, it is essential to identify the site-specific pelvic anatomical defects that cause SUI for individual patients and acknowledge the appropriate pelvic exams that can be used to diagnose these pelvic causal factors.

Based on literature research, the pelvic exams known as digital pelvic muscle strength test (Table 1) and Pelvic Organ Prolapse Quantification System (POPQ) (Table 2) were identified to be useful for assessing the weakness of pelvic floor muscles and apical vaginal ligaments that are potentially leading to the development of SUI symptoms. Both tests have demonstrated content validity, intra- and inter-user reliability, and ability to show change; however, their usefulness in assessing the pelvic causes of SUI has not been established. Pelvic muscle strength test, which uses a 9-point scale grading system, is useful for assessing pelvic muscle weakness [42]. Table 1 shows the 9-point pelvic muscle strength scale used to evaluate the pelvic muscle contraction strength for individual patients. Alternatively, POPQ is useful for objectively defining the location and extent of vaginal prolapse [63]. Its test measures include points that are measured relative to the vaginal introitus (Table 2). Their anatomic positions can be centimeters (*cm*) proximal to the introitus (negative number) or centimeters (*cm*) distal to the introitus (positive number) with the plane of vaginal introitus being defined as zero. Points *C*, *D* and *Aa* are anatomic positions that are most relevant to the current study. According to Table 2, points *C* and *D* (range: -vaginal length to + vaginal length *cm*), are used to evaluate the apical vaginal support for women without and with uteruses, respectively; in relation to urinary continence, point *Aa* (range: -3 to +3 *cm*) is used to evaluate the bladder neck support for individual women.

To improve the diagnostic accuracies of the pelvic causes of SUI, the digital pelvic muscle strength test and Pelvic Organ Prolapse Quantification System (POPQ) can be used. The current study will address the usefulness of these clinical tests in diagnosing the pelvic anatomical defects relating to SUI.

Table 1 Digital muscle strength test: A 9-point pelvic muscle strength scale [42]**.**

Scale	Score	Description
Pressure		
	0	No response
	1	Weak contraction; pressure is felt at some points along the finger surface
	2	Moderate contraction; pressure is felt all the way around the finger surface
	3	Strong contraction; pressure is felt at full circumference of the finger surface
Displacement of vertical plane		
	0	None
	1	Only the finger base(s) is pushed anteriorly and upward by the muscle
	2	The entire length of fingers are pushed anteriorly and upward by the muscle
	3	The entire length of fingers are pushed anteriorly, grasped and drawn in by the muscle
Duration in seconds		
	0	None
	1	<1 seconds
	2	>1 and <3 seconds
	3	>3 seconds

Table 2 Pelvic Organ Prolapse Quantification measurements [63]**.**

POPQ points	Definition	Levels of vaginal support
Point *C*	It is the location of the cervix or vaginal cuff (hysterectomy scar).	Level I (apical vaginal support)
Point *D*	It is the location of the posterior fornix (pouch of Douglas) in a woman who still has a cervix. For women without the cervix, point *D* will be omitted.	Level I (apical vaginal support)
Point *Aa*	It is the position of the bladder neck. It is a point located in the midline of the anterior vaginal wall 3 cm proximal to the external urethral opening. The range of position of point *Aa* relative to hymen is -3 (normal) to +3 cm.	Level II (anterior mid-vaginal support)
Point *Ba*	It is the most distal position of the upper anterior vaginal wall measured from the vaginal cuff or anterior vaginal fornix to point *Aa*. The range of position of point *Ba* relative to hymen is -3 (normal) to +3 cm.	Level II (anterior mid-vaginal support)
Point *Ap*	It is the point located in midline of posterior vaginal wall 3 cm proximal to hymen. The range of position of point *Ap* relative to hymen is -3 (normal) to +3 cm.	Level II (posterior mid-vaginal support)
Point *Bp*	It is most distal position of the upper posterior vaginal wall measured from the posterior vaginal fornix to point *Ap*. The range of position of point *Bp* relative to hymen is -3 (normal) to +3 cm.	Level II (posterior mid-vaginal support)
Genital hiatus (*gh*)	It is measured from the middle of the external urethral opening to the posterior midline hymen.	Level III (distal vaginal support)
Perineal body (*pb*)	It is measured from the posterior edge of the genital hiatus to the mid-anal opening.	Level III (distal vaginal support)
Total vaginal length (*tvl*)	It is the greatest depth of the vagina measured from the external urethral opening,	

1.5 Review of Current Biomechanical Models

Much research has been conducted to identify a technique that is useful in investigating the pelvic defects related to the development of SUI. Biomechanical modeling is found to be a useful approach for analyzing the complex behavior of a female pelvic support system under a sudden load. By modeling the behaviors of the impaired pelvic floor structures under a load (i.e. cough or Valsalva Maneuver), we can improve our understanding on the association between the pelvic floor defects and SUI.

In modeling, the pelvic support system can be divided into several pelvic elements, and through simplifying assumptions, the mechanical behavior of each element can be approximated by a mathematical equation. The geometry and the material properties specific to each element are implemented into the equation. The overall pelvic system behavior and interaction of the elements are then predicted by compiling and solving the system of equations that represent the various elements.

To date, several models relevant to the female pelvic support system have been built. The material parameters of the pelvic elements used are based on those of the female cadavers and animals (i.e. cows, rabbits), and the geometrical data are based on the MRI images of both living subjects and female cadavers. Due to the complexity of the female anatomy, some of the existing models only analyze a few pelvic structures at a time. The behaviors of the pelvic floor muscles [97-99], the vaginal wall [100], and the bladder and urethral sphincter [101-105] under exerted pressure have been separately modeled. Recently, pelvic floor models, such as those by Haridas *et al*., (2006), Bellemare *et al.*, (2007), Timm *et al.*, (2009), have been developed to incorporate more pelvic elements. Although they can demonstrate more realistic behavior of the pelvic support system, none of them focus on the role of pelvic supportive structures in urinary continence [106-108]. In 2006, Chen *et al*. constructed a 2-dimensional pelvic model that examined the interactive role of impaired pubovisceral muscles and apical vaginal ligaments in the development of anterior vaginal wall prolapse under raised IAP [109]. By incorporating the bladder neck position, the model can be used to study the effect of impaired pelvic floor muscles and apical vaginal ligaments on the bladder neck support, a major factor determining the onset of the development of SUI. In the study by Chen *et al.* (2006), the model was only used to examine the effect of primarily pelvic floor

muscle impairment and the combined effect of pelvic floor muscle and apical vaginal ligament impairment on the development of anterior vaginal wall prolapse. The effect of primarily apical vaginal ligament impairment on development of the vaginal wall prolapse has not yet been studied. It is crucial to explore how impairment of the apical vaginal impairment can contribute to pelvic floor disorders, since in recent pelvic studies, many SUI patients were demonstrated to exhibit apical vaginal prolapse [88, 110]. To improve the feasibility of the model, the current research will consider the effect of pelvic floor muscle weakness, apical vaginal ligament weakness and the combined effect of both weaknesses on the development of vaginal prolapse and SUI.

1.6 Motivation and Research Objectives

The inadequacies of the current management methods for diagnosing and treating the symptoms of Stress Urinary Incontinence for patients with coexisting pelvic organ prolapse have been previously addressed in the literature. To improve both diagnostic and treatment effectiveness for these patients, it is crucial to identify and correct the POP-related pelvic floor defects that are relevant to the development of Stress Urinary Incontinence. According to literature, weaknesses in pelvic floor musculature and cardinal and uterosacral ligaments have been identified to be potential defects leading to urinary incontinence symptoms; yet, the exact mechanisms of how these defects contribute to Stress Urinary Incontinence are still unknown. Pelvic muscle strength test and pelvic organ prolapse quantification system (POPQ) have also been found to be useful in evaluating the pelvic muscle defect, apical vaginal ligament defect and bladder neck support; however, their usefulness in assessing the pelvic causes of Stress Urinary Incontinence has not been established.

The current research aims to investigate the pelvic defects that cause Stress Urinary Incontinence for women with coexisting pelvic organ prolapse symptoms by modifying and extending a biomechanical model of the female pelvic support system previously developed by Chen *et al*. (2006). The model incorporated some of the measures of the pelvic muscle strength test and the POPQ test and used clinical data of

patients with pelvic floor disorders. By using the developed model and the clinical patient data, the thesis aims to accomplish the following objectives:

O1. Examine the contribution of pelvic musculature weakness to the development of SUI;

O2. Examine the contribution of apical vaginal ligament weakness to the development of SUI;

O3. Establish the usefulness of Pelvic Muscle Strength test and Pelvic Organ Prolapse Quantification System in diagnosing the pelvic causes of SUI.

Chapter 2

Biomechanical Model Development

A biomechanical model of a female pelvic support system was constructed to describe the mechanical interaction between the pelvic floor supportive structures (pelvic floor muscles and apical vaginal ligaments) and the pelvic organs (vagina and) during at rest and on straining conditions. The model is an extension of the pelvic model previously developed by Chen *et al*. 2006 [109]. It integrated the pelvic muscle strength score and some POPQ point measurements to improve its clinical relevance to the current pelvic exams. In terms of model development, the following sections outline i) the anatomical considerations on the modeled pelvic structures (Section 2.1), ii) the pelvic elements in the biomechanical model (Section 2.2), ii) the force-elongation equations used in the model (Section 2.3), iv) the modeling conditions and the model formulations (Section 2.4), and v) model implementation (Section 2.5).

2.1 Anatomical Considerations

Prior to the development of a biomechanical model of a female pelvic support system, some considerations relating to the pelvic anatomy are needed to be addressed. This section discusses the anatomical positions and the attachments of the pelvic floor supportive structures and the pelvic organs inside the female pelvis.

Anatomically, the pelvic floor supportive structures and pelvic organs are enclosed within the bony pelvis as shown in Figures 1 and 2. The pelvic bone, especially

the pubic bone and sacrum, provide a rigid base to which the pelvic organs are anchored and connected via the pelvic floor supportive structures (Figure 3) [20].

The pelvic floor supportive structures include: 1) pubococcygeus-puborectalis muscle (PPM); 2) iliococcygeus muscles (IM); 3) perineal membrane (PM); 4) pubocervical fascia; 5) arcus tendineus fasciae pelvis; 6) cardinal ligaments (CL); 7) uterosacral ligaments (UL). Anatomically, the pubococcygeus-puborectalis muscle band (PPM) originates from the pubic bone, and it connects to the distal end of the iliococcygeus muscles (IM). A pair of iliococcygeus muscles (IM) originates from the arcus tendineus levator ani, and they connect to the posterior end of the pubococcygeus-puborectalis muscle band (PPM). The perineal membrane originates from the pubic bone, and it inserts into the urethral and vaginal openings. The pubocervical fascia originates from the arcus tendineus fasciae pelvis, and it attaches laterally to the vaginal wall. Cardinal ligaments (CL) and uterosacral ligaments (UL) arise from the vaginal apex, and they attach the top of the vagina to the sacrum (SAC) [20].

On the other hand, the pelvic organs include: 1) vagina; 2) uterus; 3) rectum; 4) bladder; 5) urethra. Anatomically, the vagina lies on the rectum, which is supported by the iliococcygeus muscles. Its distal end is fixed at the perineal membrane, and its apical end is suspended by the cardinal and uterosacral ligaments. The uterus is situated above the vaginal apex in between the bladder and the rectum. The urinary organs, including the bladder and urethra, lie on the anterior vaginal wall. The urethra contains the bladder neck region that is normally situated at approximately 3 cm proximal to the vaginal introitus [63].

2.2 Pelvic Elements in the Biomechanical Model

Based on the knowledge of female pelvic anatomy (Section 2.2), a two-dimensional, sagittally-symmetric biomechanical model of a female pelvic support system was developed as shown in Figure 5. For simplicity, the fascial tissues and the uterus are not examined in the current study. The pelvic elements in the biomechanical model include:

- pubococcygeus-puborectalis muscle band (PPM);
- iliococcygeus muscles (IM);
- Perineal membrane (PM);
- cardinal ligament (CL);
- uterosacral ligament (UL);
- vagina (V);
- bladder (B);
- rectum (R);
- pubic bone (PB);
- sacrum (SAC).

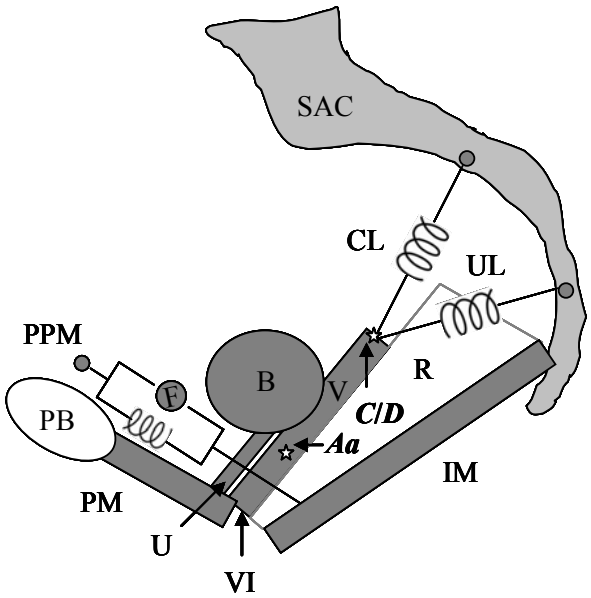

Figure 5 Biomechanical model of a female pelvic support system in standing position.
The figure shows the pelvic elements in the biomechanical model. In the model, the pubococcygeus-puborectalis is modeled as an elastic spring in parallel with an active force component (F); the cardinal ligaments and the uterosacral ligaments are modeled as passive elastic springs. Point *Aa* and point *C* or *D* (shown as stars in the figure) are POPQ points located on the vaginal wall, and they are measured relative to the vaginal introitus (VI) or vaginal opening. Point *Aa* describes the position (*cm*) of the bladder neck, and point *C*/*D* describes the position (cm) of the vaginal apex.

In the model, the pubococcygeus-puborectalis muscle band was modeled as an element having an active contractile component and a passive elastic spring component [97, 109]. When the element was activated, it was modeled to contract toward the pubic bone. The contraction strength of this element was evaluated using the 3-point scale grading system (pressure) in the Pelvic Muscle Strength test as shown in Table 1.

A pair of iliococcygeus muscles was modeled separately as an element with an active contractile component only [109]. For simplicity, it was assumed that these elements were hinged on the sacrum and that they would not passively deform. When the elements were activated, they were modeled to contract toward the sacrum.

The perineal membrane was modeled as a stationary element that provides anchorage to the distal vagina and urethra.

The cardinal and uterosacral ligaments were modeled as passive elastic spring elements [109]. These elements influenced the vaginal apex location, which is represented by POPQ point *C* or *D* (range: -vaginal length to +vaginal length). Point *C* and *D* evaluate the apical vaginal support for women without and with uteruses, respectively. Their anatomic positions can be centimeters proximal to the vaginal introitus (negative number) or centimeters distal to the introitus (positive number) with the plane of vaginal introitus being defined as zero.

The vagina was modeled as a stretchable membrane with its apex position represented by POPQ point *C* or *D*.

The bladder was modeled as an elastic and extensible sphere that stored urine [105, 106]. It was only used in modeling the equilibrium condition of a normal pelvic support system during at rest and on straining conditions. The bladder neck position was approximated by the POPQ point *Aa* (range: -3 to +3 *cm*) located on the vagina wall.

The rectum was modeled as a stationary element supported by the iliococcygeus muscles.

2.3 Force-elongation Equations

In the model, the pelvic floor muscles, cardinal and uterosacral ligaments and the vagina wall are modeled as elements that can elongate when exposed to loadings. The

mechanical behavior of the pelvic elements, including pelvic floor muscles, ligaments and vagina, is modeled by an exponential force-elongation relation, since these pelvic tissues exhibit non-linear stress-strain behavior (hyperelasticity) in mechanical tests [111-113]. The equation is as follows [109].

$$F = C1 \times (e^{C2 \times (\frac{l - l_o}{l_o})} - 1) + F_{active} \quad (1)$$

where *C1* (Newton), *C2* (dimensionless) are the material property parameters of each pelvic element; F is the force exerted onto the element; F_{active} is the active contractile force of the muscular elements (i.e. F_{active} only applies to muscular elements); l and l_o are the respective current and initial lengths of the element. Table 3 shows the material property parameters, dimensions and orientation of the modeled pelvic floor structures. The values shown were according to those reported in the literature [99, 109, 111, 112, 114, 115]. The dimensions and orientation of the pelvic floor structures are based on magnetic resonance scans of the pelvic floor regions of 21 continent females with age ranging from 46 to 71 years and 18 embalmed cadaveric pelves of normal females [99, 109, 114]. Table 4 shows the active contractile force of the pubococcygeus-puborectalis muscle band. The values shown were based on continent females with age ranging from 21 to 44 years [33, 116].

Table 3 The dimensions, orientation and material properties of the modeled pelvic floor structure.

Pelvic structures	Dimensions (cm) mean (min. – max.)	Inclination relative to horizontal (degree) mean (min. – max.)	Material parameters	Reference
Vagina	Length: 9 (6 – 12) Width: 2.6 (1.6 - 3.7)	62.4 (54.6-70.2)	*C1*: 1	[109, 111, 117]
Pubococcygeus-puborectalis band	Length: 8.7 (8 - 9.4)	28	*C1*: 1, *C2*: 7	[99, 109, 111]
Iliococcygeus	Length: 8.6 (6.3 – 10.9)	47.9 (43.1 – 52.7)	-	[99, 109]
Cardinal ligaments	Length: 7.6	81	*C1*: 4.27	[109, 111, 112]
Uterosacral ligaments	Length: 5.6 (1.12 – 10)	25	*C1*: 4.27	[109, 111, 112, 114]
Genital Hiatus	Length: 3.1 (2.1 – 4.1)	-	-	[115]

Table 4 Model variables.

Model variables	Symbol	Value mean (min. to max.)	Reference
Bladder volume	V_U	0 – 500 (mL)	[118]
Urine density	ρ_U	1000 (kg/m^3)	[105]
Valsalva Pressure	P_V	107 (61 – 153) (cmH_2O)	[21]
Muscle contractile force (at rest)	F_{3R}	2.7 (1.53 – 3.87) (N)	[33]
Muscle contractile force (on strain)	F_{3S}	6.2 (2.1 – 12.7) (N)	[116]

In terms of pelvic impairments, the impairment of the pelvic floor muscles, namely the pubococcygeus-puborectalis muscle band (PPM), is modeled by simulating the loss of its active contractile force (F_{active}) and its passive resistance properties [109],

$$F = (100 - I_{PPM})/100 \times (C1_{PPM} \times (e^{C2_{PPM} \times (\frac{l_{PPM} - l_{o,PPM}}{l_{o,PPM}})} - 1) + F_{active,PPM}) \quad (2)$$

where I_{PPM} is the percent muscle impairment ($0\% \le I_{PPM} \le 90\%$); $F_{active,PPM}$ is the active contractile force of the pubococcygeus-puborectalis muscle band (Table 4); $C1_{PPM}$ (measured in Newton) and $C2_{PPM}$ (dimensionless) are the material parameters of the pubococcygeus-puborectalis muscle band; $l_{o,PPM}$ and l_{PPM} are the original and final lengths of the muscle band, respectively (Table 3).

The impairment of each apical vaginal ligament (i.e. cardinal and uterosacral ligaments) is modeled by simulating an increase in its elasticity[2] [109],

$$F = (100 - I_{AL})/100 \times C1_{AL} \times (e^{C2_{AL} \times (\frac{l_{AL} - l_{o,AL}}{l_{o,AL}})} - 1) \quad (3)$$

where I_{AL} is the percent ligament impairment ($0\% \le I_{AL} \le 100\%$); F is the tensile force of

[2] Increase in elasticity is interpreted as tissue becoming softer (as opposed to becoming harder) and elongating more for a given force. This is equivalent to saying that in the presence of impairment, for a given strain the resistance of the tissue is reduced.

each ligament; $C1_{AL}$ (measured in Newton) and $C2_{AL}$ (dimensionless) are the material parameters of the ligament; $l_{o,AL}$ and l_{AL} are the original and final lengths of the ligaments, respectively (Table 3).

2.4 Modeling Conditions

By compiling the equations that represent the behaviors and the interactions between various pelvic elements, the model was used to simulate the behaviors of both normal and abnormal pelvic support systems in a supine position during at rest and during a valsalva maneuver. Particularly, it modeled five types of pelvic conditions, including: a) Condition 1: The behavior of a normal pelvic support system during at rest condition (Section 2.4.1); b) Condition 2: The behavior of a normal pelvic support system during a valsalva maneuver (Section 2.4.2); c) Condition 3: The behavior of a pelvic support system with impaired pelvic floor muscles during a valsalva maneuver (Section 2.4.3); d) Condition 4: The behavior of a pelvic support system with impaired cardinal and uterosacral ligaments during a valsalva maneuver (Section 2.4.4); e) Condition 5: The behavior of a pelvic support system with impaired pelvic floor muscles and impaired apical cardinal and uterosacral ligaments during a valsalva maneuver (Section 2.4.5). Conditions a and b focus on the role of pelvic floor muscles in maintaining the equilibrium state of a pelvic support system. Conditions c, d and e focus on the effect of pelvic muscle weakness and/ or apical vaginal ligament weakness on the bladder neck and vaginal apex supports. Conditions c and e are modeled based on the assumption that the vaginal prolapse is initiated by reduced pelvic muscle strength. Condition d, on the other hand, is modeled based on the assumption that the vaginal prolapse is initiated by delayed pelvic muscle contraction. The following sections will outline the five types of modeled conditions and the mathematical formulations for each modeled condition.

2.4.1 Condition 1: the behavior of a normal pelvic support system during at rest condition

The behavior of a normal pelvic support system in a supine position during at rest condition is shown in Figure 6. At rest, a normal pelvic support system has a natural

abdominal supporting force (AS) and functional pelvic floor muscles (pubococcygeus-puborectalis muscle (PPM) and iliococcygeus muscles (IM)) that provide a resting tone to help support the bladder (B) weight. The resting tone of the pelvic floor muscles, mainly the pubococcygeus-puborectalis, also aids in maintaining the genital hiatus size (GH) (Table 3). A normal pelvic support system also has intact cardinal and uterosacral ligaments that maintain vaginal apex support and promote tightening of the vagina. According to Figure 6, the normal bladder neck location at rest is represented by point Aa_{rest}, and the normal vaginal apex location at rest is represented by point C/D_{rest}.

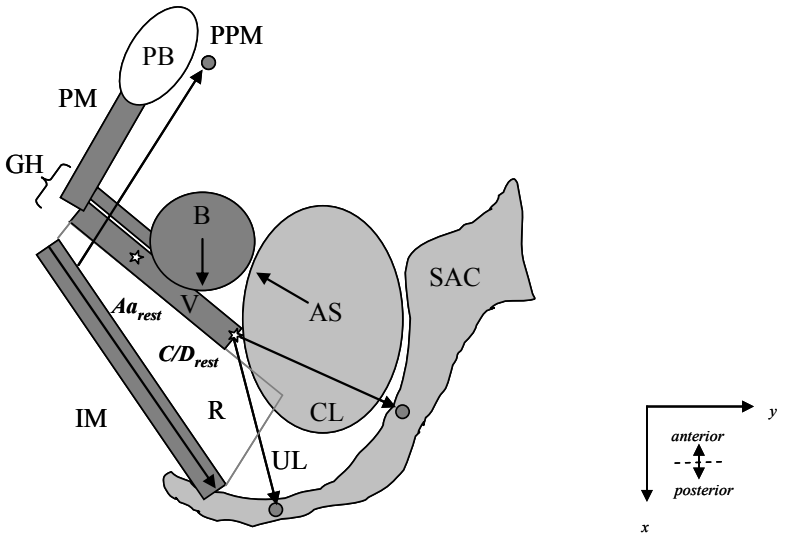

Figure 6 A normal pelvic support system in a supine position during at rest condition. Point Aa_{rest} and point C/D_{rest} are shown as stars in the figure.

Based on the description of the at-rest behavior of a normal pelvic support system, a mathematical model (Module #1) was formulated to simulate its behavior. During at rest condition, the bladder, assumed spherical, exerts a weight (F_4) that is dependent on the volume of the urine it contained,

$$F_4 = V_U \times \rho_U \times g \tag{4}$$

where V_U is the volume of urine, ρ_U is the density of urine and g is the gravity. The values for V_U and ρ_U are listed in Table 4. The bladder weight is supported by a natural abdominal supporting force and the resting tone of the pubococcygeus-puborectalis

muscle and iliococcygeus muscles. Figure 7 shows a free body diagram of the forces. From force equilibrium in *x* and *y* directions, the following equations are derived:

$$x \text{ direction:} \quad F_{1R}\cos\theta_1 + F_{2R}\cos\theta_2 - F_{3R}\cos\theta_3 + F_4 - F_{AS}\cos\theta_{AS} = 0 \tag{5}$$

$$y \text{ direction:} \quad F_{1R}\sin\theta_1 + F_{2R}\sin\theta_2 + F_{3R}\sin\theta_3 - F_{AS}\sin\theta_{AS} = 0 \tag{6}$$

where F_{1R} and Θ_1 are the resting contractile force and the inclination of the iliococcygeus muscles, respectively; F_{3R} and Θ_3 are the resting contractile force and the inclination of the pubococcygeus-puborectalis muscle band, respectively; F_{AS} and Θ_{AS} are the natural abdominal supporting force and the inclination of the natural abdominal supporting force, respectively. F_{1R} and Θ_1 are equivalent to F_{2R} and Θ_2 due to symmetry. F_{1R} and F_{2R} actually overlap in *x*-*y* plane. The slight deviation in the shown angles is to indicate that there are two forces to consider. Further, F_{3R} is a two-dimensional force, whereas F_{1R} and F_{2R} are three-dimensional forces. What are seen in Figure 7 are $F_{1R,xy}$ and $F_{2R,xy}$; but for simplicity, we refer to them as F_{1R} and F_{2R} in this text. The value of F_{1R} and F_{2R} are determined based on the force equilibrium of a normal pelvic support system in a standing position during at rest condition. The values for F_{3R} and Θ_3 are listed in Tables 3 and 4.

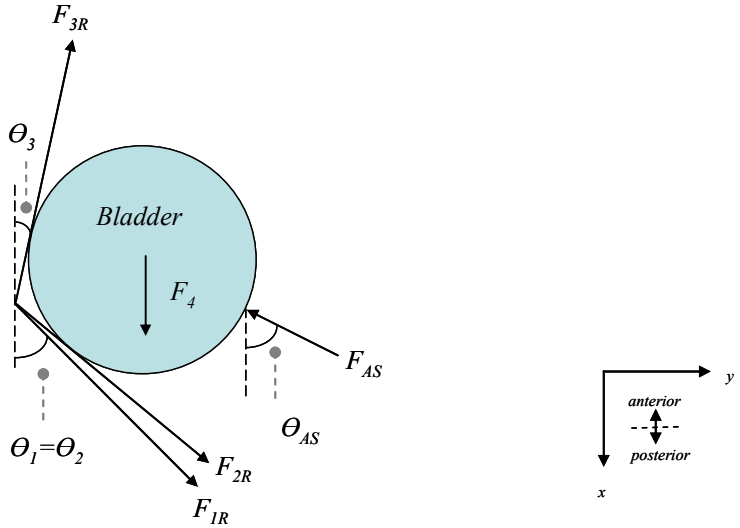

Figure 7 A free body diagram of forces for a normal pelvic support system in a supine position during at rest condition.

Based on force equilibrium, the unknown natural abdominal supporting force (F_{AS}) and

the inclination (Θ_{AS}) of the natural abdominal supporting force can be determined. The terms $\cos\Theta_{AS}$ and $\sin\Theta_{AS}$ are first isolated in equations (5) and (6), respectively, to generate the following equations (7) and (8).

$$\cos\theta_{AS} = \frac{2F_{1R}\cos\theta_1 - F_{3R}\cos\theta_3 + F_4}{F_{AS}} \tag{7}$$

$$\sin\theta_{AS} = \frac{2F_{1R}\sin\theta_1 + F_{3R}\sin\theta_3}{F_{AS}} \tag{8}$$

Then, equations 7 and 8 are substituted into the trigonometric identity, equation (9), to obtain equation (10):

$$\cos^2\theta + \sin^2\theta = 1 \tag{9}$$

$$\left(\frac{2F_{1R}\cos\theta_{1R} - F_{3R}\cos\theta_3 + F_4}{F_{AS}}\right)^2 + \left(\frac{2F_{1R}\sin\theta_{1R} + F_{3R}\sin\theta_3}{F_{AS}}\right)^2 = 1 \tag{10}$$

From equation 10, the unknown natural abdominal supporting force (F_{AS}) is obtained by the following equation,

$$F_{AS} = \sqrt{(2F_{1R}\sin\theta_1 + F_{3R}\sin\theta_3)^2 + (2F_{1R}\cos\theta_1 - F_{3R}\cos\theta_3 + F_4)^2} \tag{11}$$

Based on equation (7) and the computed value of F_{AS}, Θ_{AS} is computed as,

$$\theta_{AS} = \cos^{-1}\left(\frac{2F_{1R}\cos\theta_1 - F_{3R}\cos\theta_3 + F_4}{F_{AS}}\right) \tag{12}$$

2.4.2 Condition 2: the behavior of a normal pelvic support system during a valsalva maneuver

The behavior of a normal pelvic support system in a supine position during a valsalva maneuver is shown in Figure 8. During a valsalva maneuver, the model pelvis is

pressurized with an additional valsalva pressure (P_V), causing an increase in the intra-abdominal pressure (IAP). The red arrow shown in Figure 8 indicates the direction of valsalva pressure (P_V). A normal pelvic support system has a natural abdominal supporting force (AS) and functional pubococcgeus-puborectalis muscle (PPM) and iliococcygeus muscles (IM) that actively contract to generate force above the resting tone to support the bladder (B) weight and the valsalva pressure (P_V) [21]. The pink arrow shown in Figure 8 indicates the direction of the natural abdominal supporting force (AS). The blue arrows shown in Figure 8 indicate the direction of the contractile forces exerted by the muscles. With sufficient active muscular forces, the genital hiatus size (GH) is maintained, and so the vagina is supported by a pair of iliococcygeus muscles (IM). A normal pelvic support system also has intact apical vaginal ligaments (CL and UL) that maintain vaginal apex support and promote tightening of the vagina. The green arrows shown in Figure 8 indicate the direction of the apical vaginal ligaments. Being well-supported, the vagina is not subjected to any valsalva pressure; thus, no tension is induced in the apical portion of the vagina to strain the cardinal (CL) and uterosacral ligaments (UL). As shown in Figure 8, the normal bladder neck location during a valsalva maneuver is represented by point Aa_{strain}, and the normal vaginal apex location during a valsalva maneuver is represented by point C/D_{strain}.

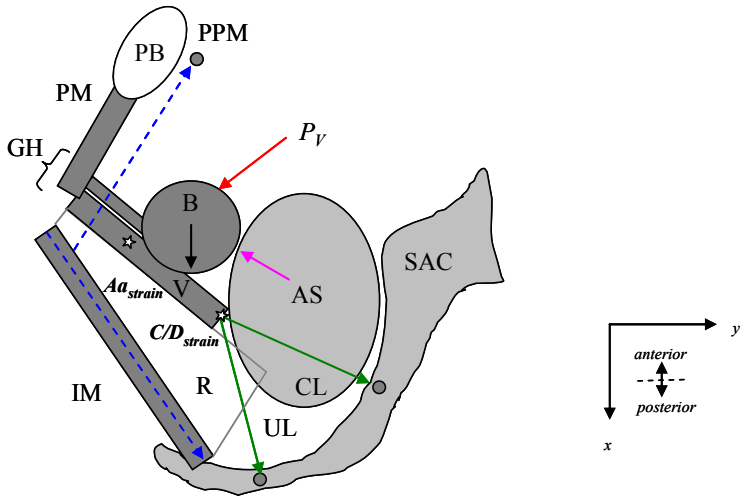

Figure 8 An activated normal pelvic support system during a valsalva maneuver. Point Aa_{strain} and point C/D_{strain} are shown as stars in the figure.

Based on the description of the on-strain behavior of a normal pelvic support system, a mathematical model (Module #2) was formulated to simulate its behavior. During a valsalva maneuver, a valsalva pressure (P_V) is applied onto the bladder. It is not too unrealistic, or at "worst" still a reasonable approximation that the valsalva pressure acts semi-spherically over the bladder. The magnitude of the valsalva force that the bladder is subjected to is then dependent on its projected cross-sectional area. The radius of the bladder is first determined based on the urine volume inside it,

$$r_B = (\frac{3 \times V_U}{4 \times \pi})^{\frac{1}{3}} \tag{13}$$

where r_B is the radius of the bladder and V_U is the volume of the urine. The values for V_U are listed in Table 4. The valsalva force, F_5, that the bladder is subjected to is computed by

$$F_5 = P_V \times \pi \times r_B^{\ 2} \tag{14}$$

where P_V is the valsalva pressure. The values for P_V are listed in Table 4. The bladder itself also exerts a weight (F_4) onto the pelvic support system, and the weight is determined using Equation 4. The direction of the bladder weight in supine position is shown in Figure 9. During a valsalva maneuver, the bladder weight (F_4) and the valsalva force (F_5) are supported by the natural abdominal supporting force and the active contractile forces of the pubococcygeus-puborectalis muscle and the iliococcygeus muscles. Figure 9 shows a free body diagram of the forces. From force equilibrium at the onset of P_V in x and y directions, noting that $F_{1S} = F_{2S}$ and $\Theta_1 = \Theta_2$, the following equations are derived:

x direction: $$2 \times F_{1S} \cos\theta_1 - F_{3S} \cos\theta_3 + F_4 + F_5 \cos\theta_5 - F_{AS} \cos\theta_{AS} = 0 \tag{15}$$

y direction: $$2 \times F_{1S} \sin\theta_1 + F_{3S} \sin\theta_3 - F_5 \sin\theta_5 - F_{AS} \sin\theta_{AS} = 0 \tag{16}$$

where F_{1S}, F_{3S}, F_5 and F_{AS} are the active contractile force of the iliococcygeus muscles, the active contractile force of the pubococcygeus-puborectalis muscle band, the valsalva force, and the natural abdominal supporting force, respectively; F_4 is the bladder weight. Θ_1, Θ_3, Θ_5, and Θ_{AS} are the inclination angles of the iliococcygeus muscles, the pubococcygeus-puborectalis muscle band, the valsalva force and the natural abdominal supporting force, respectively. The values for Θ_3 and F_{3S} are listed in Tables 3 and 4.

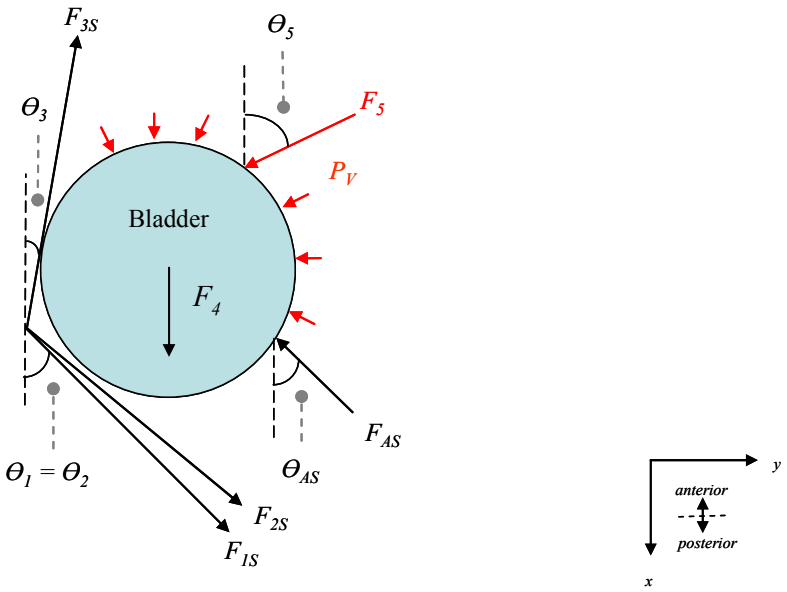

Figure 9 A free body diagram of forces for a normal pelvic support system during a valsalva maneuver.

Based on force equilibrium, the unknown contractile force exerted by the iliococcygeus muscles (F_{1S}) and the orientation of the valsalva force (Θ_5) can be determined. The terms $\cos\Theta_5$ and $\sin\Theta_5$ are first isolated in equations (15) and (16), respectively, to generate the following equations (17) and (18).

$$\cos\theta_5 = \frac{F_{3S}\cos\theta_3 - 2F_{1S}\cos\theta_1 - F_4 + F_{AS}\cos\theta_{AS}}{F_5} \qquad (17)$$

$$\sin\theta_5 = \frac{2\times F_{1S}\sin\theta_1 + F_{3S}\sin\theta_3 - F_{AS}\sin\theta_{AS}}{F_5} \tag{18}$$

Then, equations (17) and (18) are substituted into the trigonometric identity, equation (9), to yield:

$$\left(\frac{F_{3S}\cos\theta_3 - 2\times F_{1S}\cos\theta_1 - F_4 + F_{AS}\cos\theta_{AS}}{F_5}\right)^2 + \left(\frac{2\times F_{1S}\sin\theta_1 + F_{3S}\sin\theta_3 - F_{AS}\sin\theta_{AS}}{F_5}\right)^2 = 1 \tag{19}$$

Based on equation (19), F_{1S} can be solved. For clarity, we first define the lumped parameters, G, H, I, J and K as follows:

$$G = F_{3S}\cos\theta_3 - F_4 + F_{AS}\cos\theta_{AS} \tag{20}$$

$$H = -2\times\cos\theta_1 \tag{21}$$

$$I = 2\times\sin\theta_1 \tag{22}$$

$$J = F_{3S}\sin\theta_3 - F_{AS}\sin\theta_{AS} \tag{23}$$

$$K = F_5 \tag{24}$$

Substituting the parameters into equation (19), the following equation is obtained,

$$\left(\frac{G + H\times F_{1S}}{K}\right)^2 + \left(\frac{I\times F_{1S} + J}{K}\right)^2 = 1 \tag{25}$$

By expanding equation (25), the following relation is obtained,

$$G^2 + 2\times GH\times F_{1S} + (H\times F_{1S})^2 + (I\times F_{1S})^2 + 2\times IJ\times F_{1S} + J^2 = K^2 \tag{26}$$

By collecting the like terms in equation (26), a quadratic equation is generated,

$$(H^2 + I^2)\times F_{1S}^2 + (2GH + 2IJ)\times F_{1S} + (G^2 + J^2 - K^2) = 0 \tag{27}$$

The unknown contractile force exerted by the iliococcygeus muscles (F_{1S}) is then solved using the quadratic formula,

$$F_{1S} = \frac{-(2GH + 2IJ) \pm \sqrt{(2GH + 2IJ)^2 - 4(H^2 + I^2)(G^2 + J^2 - K^2)}}{2(H^2 + I^2)} \tag{28}$$

This equation yields two values for F_{1S}, and by giving consideration to the physical system, the correct one can be readily identified. Based on equation (18) and the computed value of F_{1S}, Θ_5 is computed as,

$$\theta_5 = \sin^{-1}\left(\frac{2 \times F_{1S} \sin\theta_1 + F_{3S} \sin\theta_3 - F_{AS} \sin\theta_{AS}}{F_5}\right) \tag{29}$$

2.4.3 Condition 3: the behavior of a pelvic support system with impaired pelvic floor muscles during valsalva maneuver

The behavior of a pelvic support system with impaired pelvic floor muscles in a supine position during a valsalva maneuver is shown in Figure 10. The red arrow shown in the figure indicates the direction of the valsalva pressure (P_V) applied onto the pelvic support system during a valsalva maneuver. Under a valsalva maneuver, impaired pelvic floor muscles, namely the pubococcygeus-puborectalis muscle band (PPM), can no longer generate sufficient contractile force to help sustain the equilibrium in the pelvic support system and maintain the genital hiatus size (GH) (Table 3). The genital hiatus then widens, and the iliococcygeus muscles (IM) are pushed toward the sacrum. An unsupported region in the distal anterior vaginal wall then develops, and it is subjected to the valsalva pressure. The bladder is not included in this modeled condition, since the valsalva pressure is transmitted to the unsupported region in the distal vaginal wall. As the distal vagina is tensioned by the valsalva pressure, a tensile force is also induced in the apical portion of the vaginal wall. The orange arrow shown in Figure 10 indicates the direction of this tension force. The apical cardinal (CL) and uterosacral ligaments (UL)

are now placed under tension as they resist the movement of the vaginal apex. Under tension, these ligaments elongate, and this leads to the prolapse of the vaginal apex position, as represented by point C/D_{strain} (Figure 10). At the same time when the distal vagina is tensioned, the vaginal wall itself is also elongated. As the vaginal wall elongates, the bladder neck position prolapses caudally. Taking into account the prolapse of the vaginal apex position, the bladder neck will prolapse at a greater degree. The final prolapsed position of the bladder neck, point Aa_{strain}, during a valsalva maneuver is shown in Figure 10.

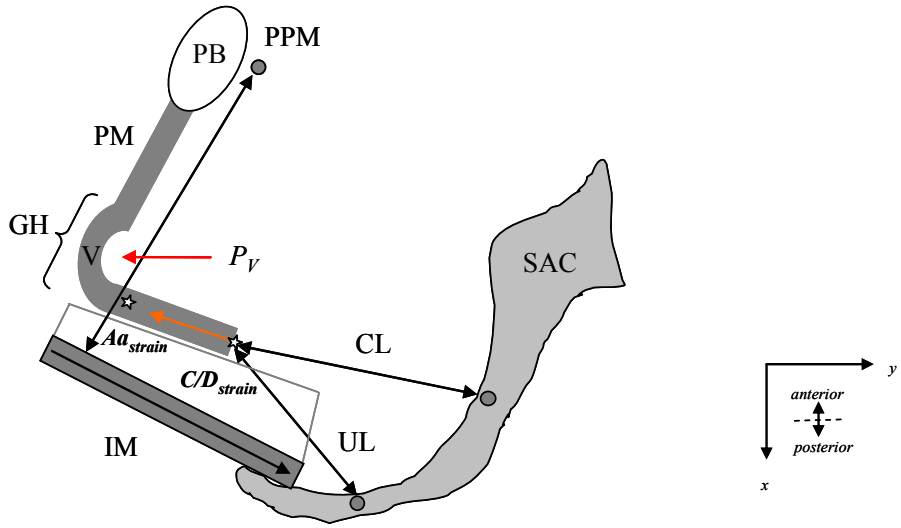

Figure 10 The behavior of a pelvic support system with impaired pelvic floor muscles during a valsalva maneuver. Point Aa_{strain} and point C/D_{strain} are shown as stars in the figure.

Based on the description of the on-strain behavior of a pelvic support system with impaired pelvic floor muscles, a mathematical model (Module #3) was formulated to simulate its behavior. When the pelvic floor muscles, namely the pubococcygeus-puborectalis muscle band, are impaired, there is a loss of both the active contractile force and its passive properties as modeled by the following equation [109],

$$F_{PPM} = (100 - I_{PPM})/100 \times (C1_{PPM} \times (e^{C2_{PPM} \times (\frac{l_{PPM} - l_{o,PPM}}{l_{o,PPM}})} - 1) + F_{3S}) \qquad (30)$$

where I_{PPM} is the percent muscle impairment ($0\% \le I_{PPM} \le 90\%$); F_{3S} is the active contractile force of the pubococcygeus-puborectalis muscle band; $C1_{PPM}$ (measured in Newton) and $C2_{PPM}$ (dimensionless) are the material parameters of the pubococcygeus-puborectalis muscle band; $l_{o,PPM}$ and l_{PPM} are the original and final lengths of the muscle band, respectively. The values of $C1_{PPM}$, $C2_{PPM}$, and $l_{o,PPM}$ are listed in Table 3. With reduced active contractile force, the pelvic floor muscles can no longer counteract the valsalva force (F_5) and maintain the normal genital hiatus size (Table 3) during a valsalva maneuver. The amount of active muscle force lost due to pelvic muscle impairment (I_{PPM} in %) is compensated by the passive component of the muscles. As the active contractile force decreased, the passive component of the muscles elongates as shown in Figure 11. The elongation is assumed to be equivalent to the length of the stretched hiatus, l_h. Based on the passive component of equation 30, l_h is computed as,

$$l_h = \left(\frac{\ln\left(\frac{I_{PPM}/100 \times F_{3S}}{(100 - I_{PPM})/100 \times C1_{PPM}} + 1\right)}{C2_{PPM}} \times l_{o,PPM}\right) \tag{31}$$

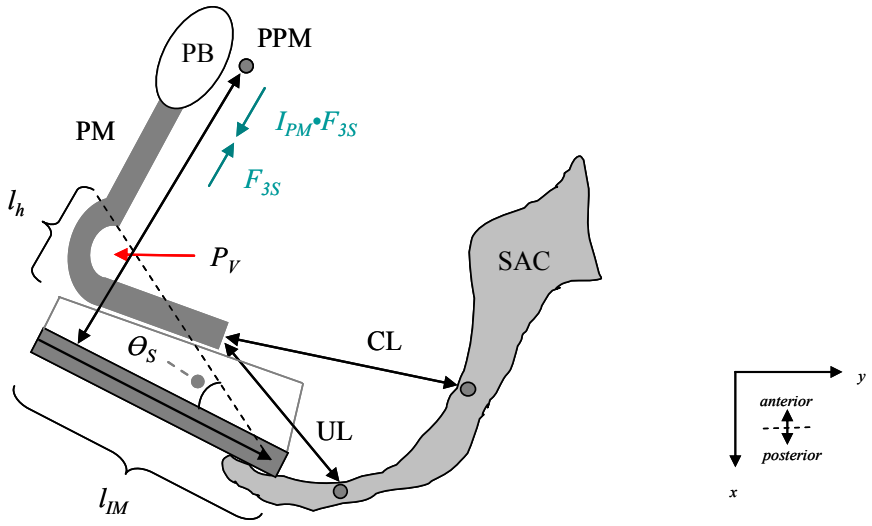

Figure 11 A diagram showing the change in the orientation of the iliococcygeus muscles (IM) and the widening of the genital hiatus (l_h) in a pelvic support system with impaired pelvic floor muscles during a valsalva maneuver.

As the hiatus widens, the distal portion of the iliococcygeus muscles is pushed toward the sacrum. With the proximal end of the iliococcygeus muscles fixed on the sacrum, the relation of arc length and radius can be used to approximate the angle, Θ_S, at which the muscles are being pushed during a valsalva maneuver (Figure 11). Θ_S is computed by assuming the arc length is the hiatus length (l_h), and the radius is the length of the iliococcygeus muscles, l_{IM},

$$\theta_S = \frac{360 \times l_h}{2\pi \times l_{IM}} \tag{32}$$

The values of l_{IM} are listed in Table 3. As the iliococcygeus muscles are pushed toward the sacrum, an unsupported region in the distal anterior vaginal wall develops. The length of the unsupported distal vaginal region ($l_{o,DV}$) is assumed to be equivalent to the hiatus length, l_h. The unsupported vaginal region is then subjected to the valsalva force (F_5) induced by the valsalva pressure (P_V). The magnitude of the valsalva force that the vaginal wall is subjected to is dependent on the cross-sectional area of the exposed vaginal wall, and it is computed by

$$F_5 = P_V \times l_h \times l_w \tag{33}$$

where l_w is the width of the vaginal wall. The values for l_w are listed in Table 3. Figure 12 shows a free body diagram of the forces acting on the distal portion of the vaginal wall. From force equilibrium between the valsalva force and the tensile forces of the vagina, F_6, in y direction, the following equation is derived:

$$y \text{ direction:} \qquad 2 \times F_6 - F_5 = 0 \tag{34}$$

Based on force equilibrium, the tensile force of the vagina (F_6) is computed by,

$$F_6 = F_5 / 2 \tag{35}$$

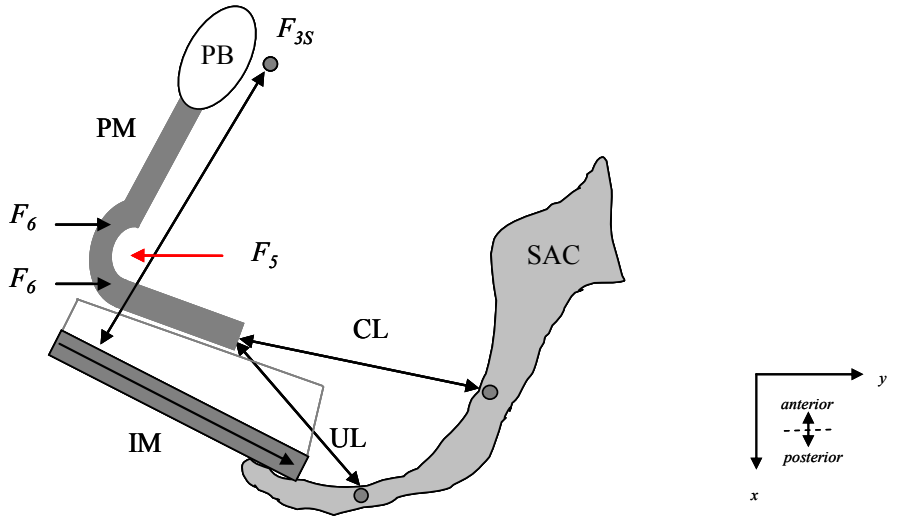

Figure 12 A free body diagram of forces acting on the unsupported distal region of the anterior vaginal wall during a valsalva maneuver.

As the distal portion of the vagina is tensioned, a tensile force is also generated at the apical portion of the vaginal wall. This tensile force is equivalent to the tensile force of the vaginal wall (F_6). The apical vaginal ligaments (cardinal and uterosacral ligaments) are now placed under tension as they resist this tensile force in an attempt to minimize the movement of vaginal apex. Figure 13 shows a free body diagram of the forces. From force equilibrium in x and y directions, the following equations are derived:

$$x \text{ direction:} \quad F_{7S}\cos(\theta_7) + F_{8S}\cos(\theta_8) - F_6\cos(\theta_6 + \theta_S) = 0 \tag{36}$$

$$y \text{ direction:} \quad F_{7S}\sin(\theta_7) + F_{8S}\sin(\theta_8) - F_6\sin(\theta_6 + \theta_S) = 0 \tag{37}$$

where F_{7S} and F_{8S} are the tensile forces of the cardinal and uterosacral ligaments, F_6 is the tensile force acting on the apical portion of the vaginal wall; Θ_6 is the inclination angle of the vagina; Θ_7 and Θ_8 are the inclination angles of the cardinal and uterosacral ligaments, respectively (Table 3). With a widened hiatus, the vagina is assumed to be pushed toward the sacrum by the same extent (Θ_S) as the iliococcygeus muscles.

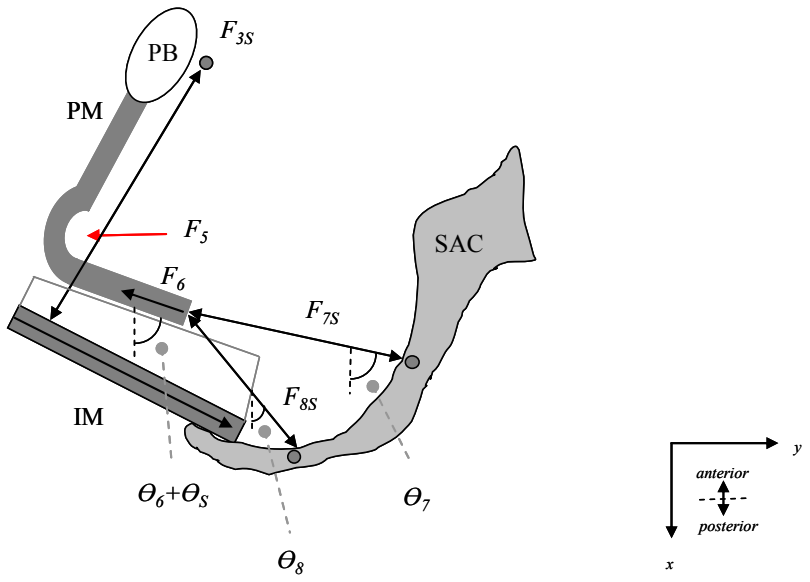

Figure 13 A free body diagram of forces acting on the upper vagina when the distal anterior vagina is tensioned during a valsalva maneuver.

Based on force equilibrium between the tensile force acting on the apical vaginal wall and the forces of the ligaments, the unknown tensile forces of the cardinal and uterosacral ligaments are computed from equations (38) and (39) as follows,

$$F_{7S} = \frac{F_6 \times \sin(\theta_6 + \theta_S) - \sin(\theta_8) \times \dfrac{F_6 \times \cos(\theta_6 + \theta_S)}{\cos(\theta_8)}}{\sin(\theta_7) - \sin(\theta_8) \times \dfrac{\cos(\theta_7)}{\cos(\theta_8)}} \tag{38}$$

$$F_{8S} = \frac{F_6 \times \cos(\theta_6 + \theta_S) - F_{7S} \times \cos(\theta_7)}{\cos(\theta_8)} \tag{39}$$

These tensile forces stretch the apical vaginal ligaments and bring about elongation of the ligaments. The change in the length of each ligament resulting from the tensile force is computed based on the force-elongation relation of the apical vaginal ligament (AL) [109],

$$F_{AL} = C1_{AL} \times (e^{C2_{AL} \times (\frac{l_{AL} - l_{o,AL}}{l_{o,AL}})} - 1) \tag{40}$$

$$dl_{AL} = l_{AL} - l_{o,AL} = \frac{\ln(\frac{F_{AL}}{C1_{AL}} + 1)}{C2_{AL}} \times l_{o,AL} \tag{41}$$

where F_{AL} is the tensile force of each ligament (F_{7S} is the tensile force of the cardinal ligaments, and F_{8S} is the tensile force of the uterosacral ligaments); dl_{AL} is the change in the length of each ligament (dl_{CL} is the change in the length of cardinal ligaments, and dl_{UL} is the change in the length of uterosacral ligaments); $l_{o,AL}$ is the original length of each ligament ($l_{o,CL}$ is the original length of cardinal ligaments and $l_{o,UL}$ is the original length of uterosacral ligaments); $C1_{AL}$ (measured in Newton) and $C2_{AL}$ (dimensionless) are the material parameters of the ligaments ($C1_{CL}$ and $C2_{CL}$ are the material parameters for cardinal ligaments, and $C1_{UL}$ and $C2_{UL}$ are the material parameters for uterosacral ligaments). The dimensions and the material parameter of the ligaments ($C1_{AL}$ value) are shown in Table 3. $C2_{AL}$ values were determined in the parameter estimation step using clinical patient data as outlined in Section 3.2. Ultimately, the elongated apical vaginal ligaments cause the vaginal apex to prolapse caudally. As the inclination of the cardinal ligament is more in-line with that of the vagina wall, it is not too unrealistic, or at "worst" still a reasonable approximation that the change in the length of the cardinal ligament approximates the change in the vagina apex position. The final vaginal apex location is represented by the location of POPQ points, C_{strain} (for female with no uterus) or D_{strain} (for female with uterus) (range: -vaginal length to +vaginal length, *cm*) measured relative to the vaginal introitus. Figure 14 shows the "at rest" and "on strain" locations of points *C* or *D*. For female with no uterus, the resulting location of C_{strain} is approximated by,

$$C_{strain} = C_{rest} + dl_{CL} \tag{42}$$

where C_{rest} and C_{strain} are the points *C* at rest and on straining, respectively. The normal location of point *C* "at rest" is approximated by – total vaginal length (i.e. - *tvl*). For

female with uterus, the resulting location of point D_{strain} is approximated by equation that is similar to equation 42. However, point D_{rest} instead of points C_{rest} will be used in the equation.

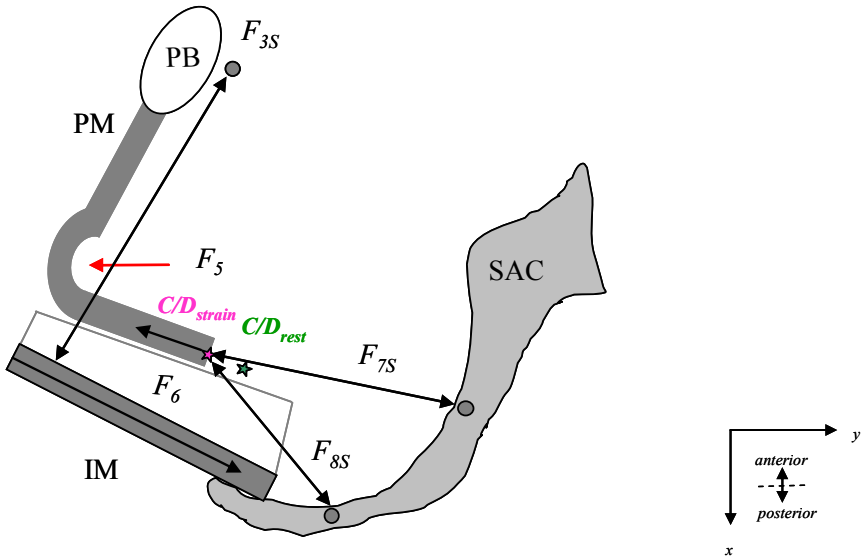

Figure 14 A diagram showing the elongated apical vaginal ligaments and the displaced vaginal apex location during a valsalva maneuver. Point C/D_{rest} and point C/D_{strain} are shown as stars in the figure.

At the same time as the distal vaginal wall is tensioned, the vaginal wall is also elongated, and this brings about a change in the bladder neck position. The change in the bladder neck position ($dl_{BN,V}$) caused by elongation of the vaginal wall is computed based on the force-elongation relation of the vagina (V) [109],

$$F_6 = C1_V \times (e^{C2_V \times (\frac{dl_{BN,V}}{l_{o,BN,V}})} - 1) \tag{43}$$

$$dl_{BN,V} = \frac{\ln(\frac{F_6}{C1_V} + 1)}{C2_V} \times l_{o,BN,V} \tag{44}$$

where $C1_V$ (measured in Newton) and $C2_V$ (dimensionless) are the material parameters of vagina; $l_{o,BN,V}$ is the original length measured from the bladder neck position to the vaginal apex. The value of $C1_V$ is listed in Table 3. $C2_V$ values were determined in the

parameter estimation step using clinical patient data as outlined in Section 3.2. However, as the vaginal apex has also prolapsed caudally, the change in the vaginal apex position also contributes to the change in the bladder neck position. The final bladder neck position is represented by the location of the POPQ point Aa_{strain} (range: -3 to +3 *cm*) measured relative to the vaginal introitus. Figure 15 shows the "at rest" and "on strain" locations of point *Aa*. The location of point Aa_{strain} is approximated by,

$$Aa_{strain} = Aa_{rest} + dl_{BN,V} + dl_{CL} \tag{45}$$

where Aa_{rest} and Aa_{strain} are the points *Aa* at rest and on straining, respectively. The normal location of point *Aa* "at rest" is shown in Table 2.

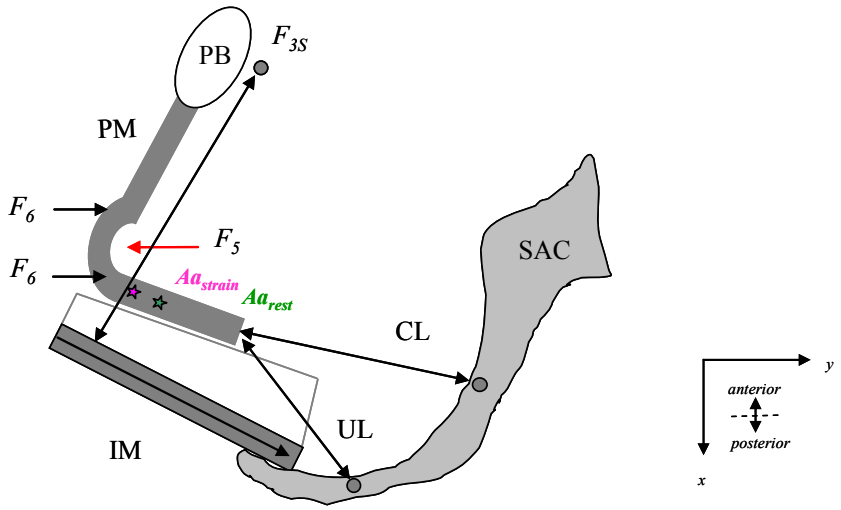

Figure 15 A diagram illustrating the elongated vagina and the displaced bladder neck location during a valsalva maneuver. Point Aa_{rest} and point Aa_{strain} are shown as stars in the figure.

2.4.4 Condition 4: the behavior of a pelvic support system with impaired cardinal and uterosacral ligaments during a valsalva maneuver

The behavior of a pelvic support system with impaired cardinal and uterosacral ligaments in a supine position during a valsalva maneuver is shown in Figure 16. The red arrow shown in the figure indicates the direction of the valsalva pressure (P_V) applied

onto the pelvic support system during a valsalva maneuver. When the pelvic support system with impaired apical vaginal ligaments is subjected to the valsalva pressure (P_V), and the pelvic floor muscles exhibited a delayed contraction when the pressure is exerted, the pressure is applied onto the distal portion of the vaginal wall. As the distal vagina is tensioned by the valsalva pressure, a tensile force (orange arrow) is also induced in the apical portion of the vaginal wall. This places the apical vaginal ligaments under tension as they resisted the movement of the vaginal apex. Under tension, these ligaments elongate, and with impairment, they will elongate at a greater extent, leading to the prolapse of the vaginal apex position as represented by point C/D_{strain} (Figure 16). At the same time when the distal vagina is tensioned, the vaginal wall itself is also elongated. As the vaginal wall elongates, the bladder neck position prolapses caudally. Taking into account the prolapse of the vaginal apex position, the bladder neck will prolapse at a greater degree. The final prolapsed position of the bladder neck, point Aa_{strain}, during a valsalva maneuver is shown in Figure 16.

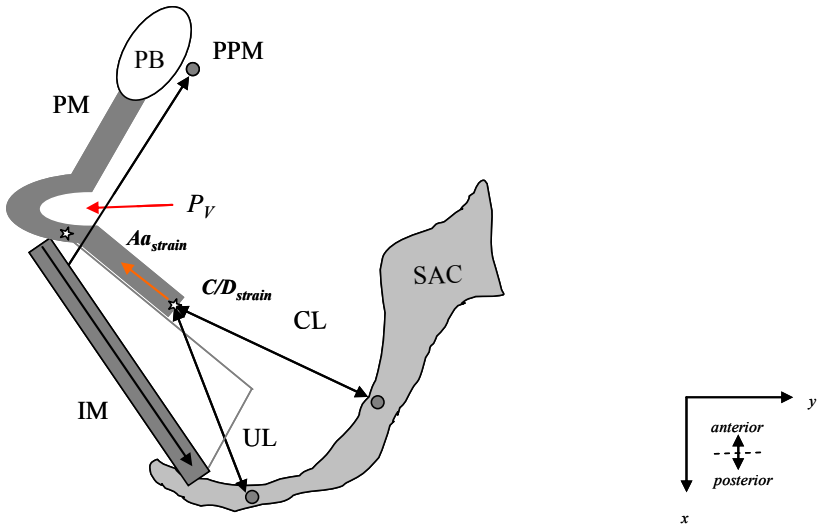

Figure 16 The behavior of a pelvic support system with apical vaginal ligament impairment during a valsalva maneuver. Point Aa_{strain} and point C/D_{strain} are shown as stars in the figure.

Based on the description of the on-strain behavior of a pelvic support system with impaired cardinal and uterosacral ligaments, a mathematical model (Module #4) was formulated to simulate its behavior. During a valsalva maneuver, a valsalva pressure (P_V)

is exerted onto the pelvic support system. In conditions when the pelvic floor muscles exhibit a delayed contraction at the time the valsalva pressure is exerted, the pressure is applied onto the genital hiatus, tensioning the distal portion of the vaginal wall. The normal genital hiatus size is shown in Table 3. The valsalva force (F_5) that the distal vaginal wall is subjected to is computed by equation 33, and based on the force equilibrium between the valsalva force and the tensile forces of the vagina, F_6, the tensile force of the vagina is computed using equations 34 to 35. As the distal vagina is tensioned, a tensile force is generated at the apical portion of the vaginal wall; this places the impaired apical vaginal ligaments under tension as they resisted the movement of the vaginal apex. Figure 17 shows a free body diagram of the forces. From force equilibrium in x and y directions, the following equations are derived:

$$x \text{ direction:} \quad F_{7S}\cos(\theta_7) + F_{8S}\cos(\theta_8) - F_6\cos(\theta_6) = 0 \tag{46}$$

$$y \text{ direction:} \quad F_{7S}\sin(\theta_7) + F_{8S}\sin(\theta_8) - F_6\sin(\theta_6) = 0 \tag{47}$$

where F_{7S} and F_{8S} are the tensile forces of the cardinal and uterosacral ligaments, F_6 is the tensile force of the vagina; Θ_6 is the inclination angle of the vagina; Θ_7 and Θ_8 are the inclination angles of the cardinal and uterosacral ligaments, respectively (Table 3). Based on the force equilibrium between the tensile force acting on the apical portion of the vaginal wall (F_6) and the forces of the cardinal (F_{7S}) and uterosacral ligaments (F_{8S}), the tensile forces of the ligaments (F_{7S}, F_{8S}), the unknown tensile forces of the cardinal and uterosacral ligaments are computed from equations (48) and (49) as follows;

$$F_{7S} = \frac{F_6 \times \sin(\theta_6) - \sin(\theta_8) \times \dfrac{F_6 \times \cos(\theta_6)}{\cos(\theta_8)}}{\sin(\theta_7) - \sin(\theta_8) \times \dfrac{\cos(\theta_7)}{\cos(\theta_8)}} \tag{48}$$

$$F_{8S} = \frac{F_6 \times \cos(\theta_6) - F_{7S} \times \cos(\theta_7)}{\cos(\theta_8)} \tag{49}$$

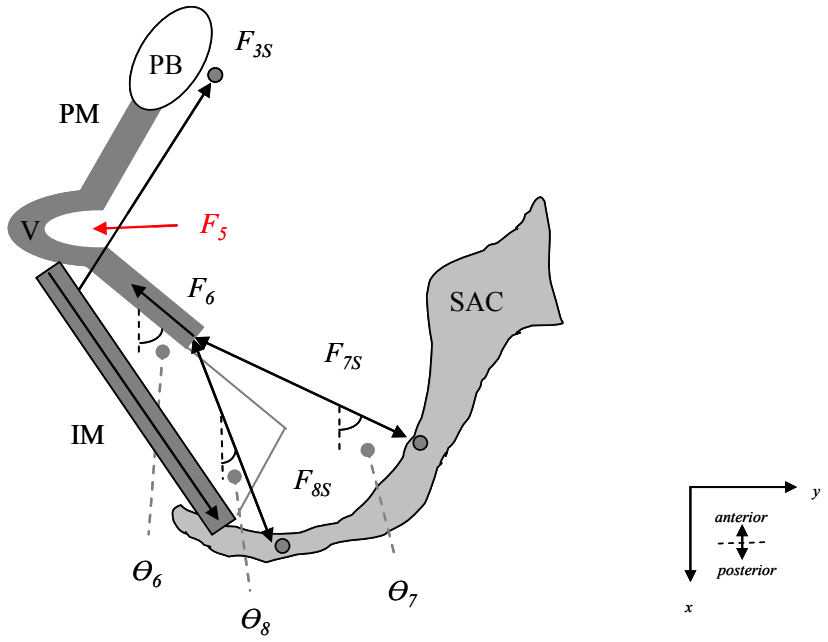

Figure 17 A free body diagram of forces acting on the upper vagina when the distal anterior vagina is tensioned during a valsalva maneuver.

These tensile forces cause stretching of the ligaments, and the extent of stretching is also dependent on the degree of ligament impairment. The impairment of each apical vaginal ligament (AL) is modeled by simulating an increase in its elasticity. The final elongated length of each apical vaginal ligament (AL) resulting from the tensile force of the ligament (F_{7S} or F_{8S}) is computed based on the force-elongation relation of the apical vaginal ligaments,

$$F_{AL} = (100 - I_{AL})/100 \times (C1_{AL} \times (e^{C2_{AL} \times (\frac{l_{AL} - l_{o,AL}}{l_{o,AL}})} - 1)) \quad (50)$$

$$dl_{AL} = l_{AL} - l_{o,AL} = \frac{\ln(\frac{F_{AL}}{(100 - I_{AL})/100 \times C1_{AL}} + 1)}{C2_{AL}} \times l_{o,AL} \quad (51)$$

where F_{AL} is the tensile force of each ligament (F_{7S} is the tensile force of cardinal ligaments, and F_{8S} is the tensile force of the uterosacral ligaments); I_{AL} is the percent ligament impairment ($0\% \leq I_{AL} \leq 100\%$); $C1_{AL}$ (measured in Newton), $C2_{AL}$

(dimensionless) are the material parameters of the ligament ($C1_{CL}$ and $C2_{CL}$ are the material parameters for cardinal ligaments, and $C1_{UL}$ and $C2_{UL}$ are the material parameters for uterosacral ligaments); dl_{AL} is the change in the length of each ligament (dl_{CL} is the change in the length of cardinal ligaments, and dl_{UL} is the change in the length of uterosacral ligaments); $l_{o,AL}$ and l_{AL} are the original and final lengths of the ligaments, respectively ($l_{o,CL}$ is the original length of cardinal ligaments and $l_{o,UL}$ is the length of uterosacral ligaments). The dimensions and the material parameter of the ligaments ($C1_{AL}$ value) are shown in Table 3. $C2_{AL}$ values were determined in the parameter estimation step using clinical patient data as outlined in Section 3.2. As the apical vaginal ligaments elongate, the vaginal apex prolapses caudally. As the inclination of the cardinal ligament is more in-line with that of the vagina wall, it is not too unrealistic, or at "worst" still a reasonable approximation that the change in the length of the cardinal ligament approximates the change in the vagina apex position. The final vaginal apex position is represented by the the location of POPQ point C_{strain} (for patient with no uterus) or D_{strain} (for patient with uterus) (range: -vaginal length to +vaginal length, *cm*) measured relative to the vaginal introitus. Figure 18 shows the "at rest" and "on strain" locations of point C or D in a pelvic support system with primarily apical vaginal ligament impairment.

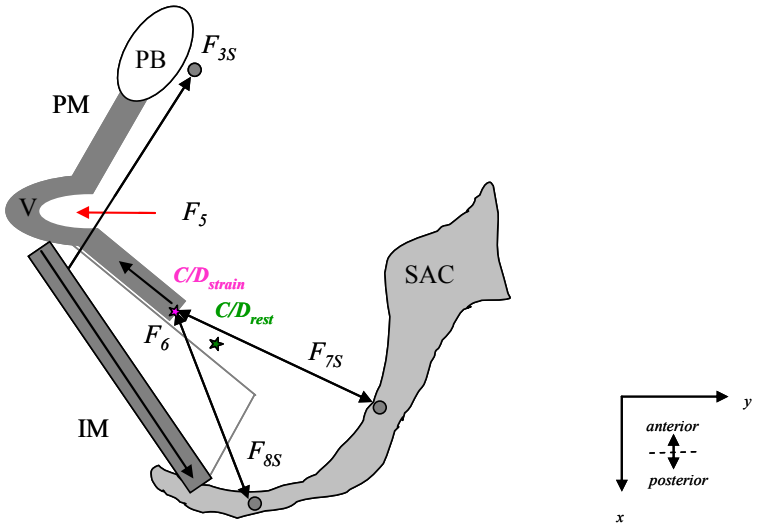

Figure 18 A diagram showing the elongated apical vaginal ligaments and the displaced vaginal apex location during a valsalva maneuver. Point C/D_{rest} and point C/D_{strain} are shown as stars in the figure.

For female with no uterus, the resulting location of C_{strain} is approximated by,

$$C_{strain} = C_{rest} + dl_{CL} \tag{52}$$

For female with uterus, the resulting location of point D_{strain} is approximated by equation that is similar to equation 52. However, point D_{rest} instead of points C_{rest} will be used in the equation. At the same time as the distal vaginal wall is tensioned, the vaginal wall itself is also elongated, and this brings about a change in the bladder neck position. The change in the bladder neck position ($dl_{BN,V}$) caused by elongation of the vaginal wall is determined using equations 43 to 44. However, as the vaginal apex has also prolapsed caudally, the change in the vaginal apex position also contributes to the change in the bladder neck position. The final bladder neck position is represented by the location of the POPQ point Aa_{strain} (range: -3 to +3 *cm*) measured relative to the vaginal introitus. Figure 19 shows a free body diagram of the forces, and the "at rest" and "on strain" locations of point *Aa* in a pelvic support system with primarily apical vaginal ligament impairment.

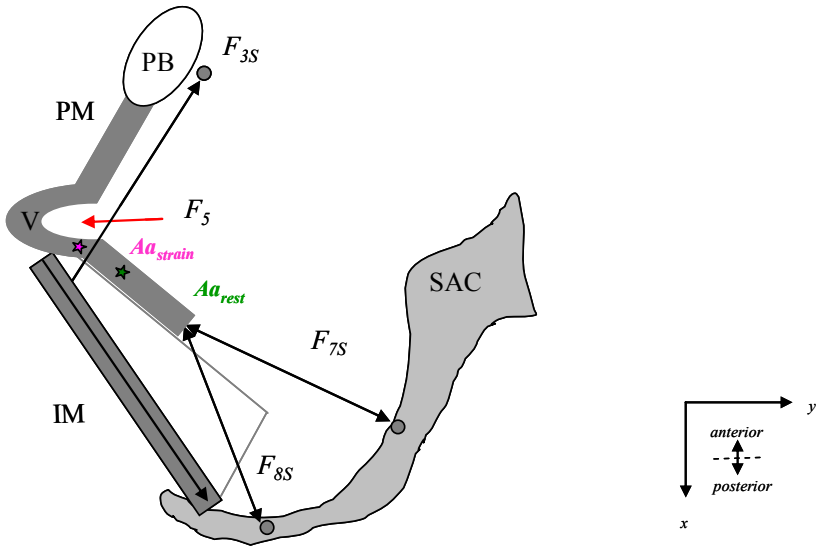

Figure 19 A diagram showing the free body diagram of force acting on the unsupported distal region of the anterior vaginal wall. The figure also shows the displaced bladder neck location during a valsalva maneuver. Point Aa_{rest} and point Aa_{strain} are shown as stars in the figure.

The resulting location of point Aa_{strain} is approximated by,

$$Aa_{strain} = Aa_{rest} + dl_{BN,V} + dl_{CL} \tag{53}$$

where Aa_{rest} and Aa_{strain} are the points Aa at rest and on straining, respectively. The location of point Aa "at rest" is shown in Table 2.

2.4.5 Condition 5: the behavior of a pelvic support system with impaired pelvic floor muscles and impaired cardinal and uterosacral ligaments during a valsalva maneuver

The behavior of a pelvic support system with impaired pelvic floor muscles and impaired apical cardinal and uterosacral ligaments in a supine position during a valsalva maneuver can also be illustrated by Figure 10. The behavior of this type of pelvic support system is similar to that with primarily pelvic floor muscle impairment (Section 2.4.3), except the apical vaginal ligament impairment is incorporated. With the incorporation of the apical vaginal ligament impairment, the apical vaginal ligaments are stretched at a greater extent, leading to more prolapsed bladder neck and vaginal apex positions.

The mathematical formulation for simulating the behavior a pelvic support system with both pelvic floor muscle and apical vaginal ligament impairments (Module #5) is developed by integrating the formulations of a pelvic support system with primarily pelvic muscle impairment (Section 2.4.3) and a pelvic support system with primarily cardinal and uterosacral impairments (Section 2.4.4).

2.5 Model Implementation

The formulated model was implemented in Matlab (The MathWorks Inc., Natick, MA) to allow simulations of the behaviors of both normal and abnormal female pelvic support systems during at rest condition and during a valsalva maneuver. To simulate a normal valsalva maneuver, the pelvic model is pressurized with 107 cmH_2O of valsalva

pressure (Table 4). To approximate the residual volume of a clinically "empty bladder", a urine volume of 100 *mL* was used in the model. In model simulations, variables, including bladder volume, valsalva pressure, muscle contractile force and pelvic floor structures' inclinations, dimensions and material parameters are used as model inputs. Table 3 and Table 4 show the mean values and ranges of these input variables.

Chapter 3

Clinical Application

Clinical pelvic data of patients with pelvic floor disorders were collected from an existing medical database. The clinical data were implemented into the biomechanical model to perform parameter estimation for clinical patients. The estimated parameters were then used in the model to perform modeling of general behaviors of both normal and abnormal female pelvic support systems during at rest condition and during a valsalva maneuver and modeling of pelvic floor defects for individual clinical patients. The following sections outline the details of clinical patient data collection (Section 3.1), parameter estimation (Section 3.2), modeling of general behaviors of normal and abnormal pelvic support systems (Section 3.3) and modeling of pelvic floor defects for clinical patients (Section 3.4).

3.1 Clinical Patient Data Collection

Clinical patient data were collected from an existing medical database previously used for *The PESSRI study*, a multi-centered randomized crossover trial that compared the support effectiveness of the ring pessary to the Gellhorn pessary [88]. All participants were given informed consent in the previous study and the Providence Health Care Research Ethics Board provided ethical approval for the use of the data. The database contains clinical data from 135 female patients with a mean age of 61 (30-89) and parity of 3 (0 to 11). The patients exhibited pelvic organ prolapse, and many of them had coexisting urinary incontinence symptoms. The median POPQ stage was determined to

be III, including 48% with stage II, 42% with stage III, and 10% with stage IV. Anterior vaginal prolapse predominated in 51%, apical vaginal prolapse in 34%, posterior vaginal prolapse in 10%, and no site predominated in 5% of the patients. 82% of the patients had postmenopausal status, and 45% of them had hysterectomy (removal of uterus). The data were based on validated pelvic floor distress inventory and impact questionnaires. To comply with the requirements of patient confidentiality, each patient was assigned a random identification number.

To assess the effect of childbirth on pelvic floor integrity and to examine the most natural cases of pelvic defects, the current study only used the data from patients who were parous and had no prior incontinence and prolapse surgeries. From each of these selected patients, the anatomical measures, including POPQ points (points *Aa* and *C* or *D*), total vaginal length (*tvl*) and muscle strength score, were collected. The POPQ points, vaginal lengths and muscle strength scores were measured when patients, with empty bladders, were performing valsalva maneuver in supine positions. Based on the POPQ points, the patients with POPQ data that cannot be reasonably applied to the force-elongation formula were also eliminated, and they are patients who exhibit severe pelvic organ prolapse symptoms.

Using the collected clinical data, the selected patients were then classified into 3 groups: those who had primarily pelvic floor muscle impairment (Group 1), those who had primarily apical vaginal ligament impairment (Group 2), and those who had both pelvic floor muscle impairment and apical vaginal ligament impairment (Group 3).

To identify the patients with primarily pelvic floor muscle impairment (Group 1), the pressure component (3-point scale) of the muscle strength score was used. Based on the score, the percent impairment of the pelvic floor muscles (I_{PPM}) was determined for each selected patient (Table 1). It was assumed that a decrease in each point of the pressure score corresponds to about 30% of the pelvic floor muscle impairment. Based on the computed I_{PPM} values, the patients with pelvic muscle impairment ($I_{PPM} > 0\%$) were identified and classified as Group 1 patients. According to their I_{PPM} values, these patients are further classified into 3 groups: those with 30% (Group 1A, sample size = 12), 60% (Group 1B, sample size = 11) or 90% percent (Group 1C, sample size = 3)

pelvic floor muscle impairment. As there are no imaging evidence of damages in their apical vaginal ligaments, all Group 1 patients were assumed to have normal apical vaginal ligaments. The prolapsed vaginal apex (points *C* or *D* approaching + vaginal length in *cm*) conditions diagnosed in these patients were assumed to be primarily caused by weakened pelvic floor muscles. The clinical data for this group of patients (Group 1) were used in Module #3 to model the behaviors of the pelvic support systems with primarily pelvic muscle impairment (i.e. pelvic condition 3).

To identify the patients with primarily apical vaginal ligament impairment (Group 2) and patients with both apical vaginal ligament and pelvic floor muscle impairments (Group 3), the POPQ point *C* or *D* and the total vaginal length (*tvl*) are used. Using the POPQ data, the percent of apical vaginal ligament impairment (I_{AL}) was computed for each patient using the following equation,

$$I_{AL} = \frac{C \text{ or } D + tvl}{2 \times tvl} \times 100 \tag{54}$$

where I_{AL} is the percent ligament impairment ($0\% \le I_{AL} \le 100\%$). Based on the computed I_{AL} values, the patients with apical vaginal ligament weakness ($I_{AL} > 0\%$) were identified. For patients who had apical vaginal ligament weakness, their corresponding percent pelvic muscle impairment (I_{PPM}) was also determined based on the pressure component (3-point scale) of their muscle strength scores. According to the I_{PPM} values, these patients were further classified into two groups: those who had normal pelvic floor muscles (Group 2, $I_{PPM} = 0\%$) and those who had impaired pelvic floor muscles (Group 3, $I_{PPM} > 0\%$). Group 2 patients were classified as those with primarily apical vaginal ligament impairment (sample size = 5), and they have defective apical vaginal ligaments. The prolapsed vaginal apexes (points *C* or *D* approaching + vaginal length in *cm*) diagnosed in these patients were assumed to be caused by weakened apical vaginal ligaments. The clinical data for this group of patients (Group 2) were used in Module #4 to model the behaviors of the pelvic support systems with primarily apical vaginal ligament impairment (i.e. pelvic condition 4). Group 3 patients, on the other hand, were classified as those with both pelvic floor muscle and apical vaginal ligament

impairments, and they are the same patients as those in Group 1. Based on the percent pelvic muscle impairment (I_{PPM}), the patients in Group 3 were further subdivided into 3 groups: those with 30% (Group 3A, sample size = 12), 60% (Group 3B, sample size = 11) or 90% (Group 3C, sample size = 3) coexisting pelvic muscle impairment. The prolapsed vaginal apexes (points *C* or *D* approaching + vaginal length in *cm*) diagnosed in these patients were assumed to be caused by both weakened pelvic floor muscles and apical vaginal ligaments. The clinical data for this group of patients (Group 3) were used in Module #5 to model the behaviors of the pelvic support systems with both pelvic floor muscle and apical vaginal impairments (i.e. pelvic condition 5).

3.2 Parameter Estimation

The parameters, namely $C2_V$ and $C2_{AL}$, were determined for individual clinical patients using the clinical patient data and the biomechanical model. $C2_V$ and $C2_{AL}$ are material parameters that describe the respective stiffness properties of the vagina (V) and cardinal and uterosacral ligaments (AL), and they are used in the exponential force-elongation relation to model the mechanical behaviors of vagina (Equation 43) and cardinal and uterosacral ligaments (Equations 40 and 50), respectively. In parameter estimation, all patients were assumed to have a fixed but typical bladder volume, valsalva pressure, pelvic floor structures' inclinations, dimensions and material parameters ($C1_V$ and $C1_{AL}$) during a valsalva maneuver (Tables 3 and 4). For each patient with primarily pelvic floor muscle impairment (Group 1), the POPQ measures (points *Aa* and *C* or *D*) and the percent muscle impairment value were implemented into the Module #3 (ie. Module #3 simulates the behavior of a pelvic support system with primarily pelvic muscle impairment) to compute the material parameters ($C2_V$ and $C2_{AL}$) specific to the individual. For each patient with primarily apical vaginal ligament impairment (Group 2), the POPQ measures (points *Aa* and *C* or *D*) and the percent ligament impairment value were implemented into Module #4 (ie. Module #4 simulates the behavior of a pelvic support system with primarily cardinal and uterosacral ligament impairment) to compute the material parameters ($C2_V$ and $C2_{AL}$) specific to the individual. For each

patient with both pelvic floor muscle and apical vaginal ligament impairments, the POPQ measures (points *Aa* and *C* or *D*) and the percent muscle and ligament impairment values were implemented into Module #5 (ie. Module #5 simulates the behavior of a pelvic support system with both pelvic muscle and cardinal and uterosacral ligament impairment) to compute the material parameters ($C2_V$ and $C2_{AL}$) specific to the individual.

For patients with primarily pelvic floor muscle impairment (Group 1), statistical Mann-Whitney *U*-test tests were performed to detect differences of the mean $C2_V$ and $C2_{AL}$ values between patients with 30% (Group 1A) and 60% (Group 1B) pelvic floor muscle impairment. $P < 0.05$ was considered statistically significant. The parameter values of patients with 90% (Group 1C) pelvic floor muscle impairment are not compared in the statistical test due to the low number of sample group size (sample size = 3). The computed material parameters were then plotted against the percentages of pelvic muscle impairment, and the plots were analyzed.

For patients with primarily apical vaginal ligament impairment (Group 2) and patients with pelvic floor muscle and apical vaginal ligament impairments (Group 3), Mann-Whitney *U*-test was performed to detect differences of the mean $C2_V$ and $C2_{AL}$ values between the two patient groups. $P < 0.05$ was considered statistically significant. The parameter values of patients with 90% (Group 3C) pelvic floor muscle impairment are yet again not compared in the statistical test due to the low number of sample group size (sample size = 3). For Groups 2 and 3 patients, the computed material parameters were then plotted against the percentages of apical vaginal ligament and pelvic floor muscle impairment, and the plots were analyzed.

3.3 Modeling Normal and Abnormal Pelvic Support Systems

The general behaviors of both normal and abnormal female pelvic support systems during at rest condition and during a valsalva maneuver were simulated using the biomechanical model along with the model inputs listed in Tables 3 and 4 and the estimated material parameters ($C2_V$ and $C2_{AL}$) of the clinical patients. In terms of

modeling the normal pelvic support system behavior, the force equilibrium between the pelvic floor structures was performed, and the effect of functional pelvic floor muscles on the bladder neck and vaginal apex supports were evaluated for clinical patients. Model simulations were run with impairments of 0% decrements (I_{PPM}) in the contractile force that the pelvic floor muscles could generate and 0% decrease in the resistance of apical vaginal ligaments. The outcome measures include natural abdominal supporting force (F_{AS}), the inclination of the natural abdominal supporting force (Θ_{AS}), the contractile force of the iliococcygeus muscles (F_{1S}), the orientation of the valsalva force (Θ_5), the bladder neck positions (points *Aa* in *cm*) and the vaginal apex positions (points *C* or *D* in *cm*). In terms of modeling the abnormal pelvic support system behavior, the force equilibrium between the pelvic floor structures was performed and the effect of pelvic floor defects, mainly pelvic floor muscle weakness and apical vaginal ligament weaknesses, on the bladder neck and vaginal apex supports were assessed. To simulate the general behavior of an abnormal pelvic support system with pelvic floor muscle weakness, model simulations were run with impairments of 30%, 60%, and 90% decrements (I_{PPM}) in the contractile force that the pelvic floor muscles could generate. In this simulation, the mean values of the estimated tissue parameters, $C2_V$ and $C2_{AL}$, for patients with primarily pelvic floor muscle impairment (Group 1) were used. To simulate the general behavior of an abnormal pelvic support system with apical vaginal ligament weakness, model simulations were run with impairment of 20% to 100% decreases (I_{AL}) in the resistance of the apical vaginal ligaments. In this simulation, the mean values of the estimated tissue parameters, $C2_V$ and $C2_{AL}$, for patients with apical vaginal ligament impairment (Groups 2 and 3) were used. The outcome measures, mainly the bladder neck positions (points *Aa*) and vaginal apex positions (points *C* or *D*), were estimated by the model. They were then collected and analyzed.

3.4 Modeling Pelvic Floor Defects

The contribution of pelvic floor muscular weakness to the development of SUI was assessed for patients with primarily pelvic floor muscle impairment (Group 1) using

Module #3 (i.e. Module #3 simulates the behavior of a pelvic support system with primarily pelvic floor muscle impairment) and the data for Group 1 patients. For each patient, the input percentage of pelvic muscle impairment was varied, and the patient-specific material parameters ($C2_V$ and $C2_{AL}$) were implemented into Module #3 to assess the effect of varied degree of muscle impairment on the changes in the bladder neck support conditions. For instance, for patients who initially had 30% pelvic muscle impairment (Group A), the changes in the bladder neck locations relative to the vaginal introitus were assessed as the percent muscle impairment increased to 60% and 90%; for patients who initially had 60% pelvic muscle impairment (Group B), the changes in the bladder neck locations relative to the vaginal introitus were assessed as the percent muscle impairment increased to 90% and decreased to 30%. In addition to the bladder neck locations, the changes in the vaginal apex locations were assessed when the percentage of pelvic muscle impairment was varied.

On the other hand, the contribution of cardinal and uterosacral ligament weakness to the development of SUI was assessed for patients with primarily apical vaginal ligament impairment (Group 2) using Module #4 (i.e. Module #4 simulates the behavior of a pelvic support system with primarily cardinal and uterosacral ligament impairment) and the data for Group 2 patients. As well, the contribution of cardinal and uterosacral ligament weakness to the development of SUI was assessed for patients with both pelvic floor muscle and apical vaginal ligament impairments (Group 3) using Module #5 (i.e. Module #5 simulates the behavior of a pelvic support system with both pelvic muscle and cardinal and uterosacral ligament impairment) and the data for Group 3 patients. For each patient, the input percentage of apical vaginal ligament impairment was varied, and the patient-specific material parameters were implemented into the model to assess the effect of varied degree of ligament impairment on the changes in the bladder neck support conditions. For instance, for patients who initially had 10% apical vaginal ligament impairment, the changes in the bladder neck locations relative to the vaginal introitus were assessed as the percent ligament impairment was changed to 0%, 20%, 40%, 60%, 80% and 100%; for patients who initially had 50% ligament impairment, the changes in the bladder neck locations relative to the vaginal introitus were assessed as the percent ligament impairment was changed to 0%, 20%, 40%, 60%, 80% and 100%; for

patients who initially had 100% ligament impairment, the changes in the bladder neck locations relative to the vaginal introitus were assessed as the percent ligament impairment was changed to 0%, 20%, 40%, 60%, and 80%. In addition to the bladder neck locations, the vaginal apex locations were evaluated when the percentage of ligament impairment was varied.

The modeled outcome measures were points *Aa* (i.e. in centimeters), which describe the bladder neck support, and points *C* or *D* (in centimeters), which describe the apical vaginal support. These outcome measures were then plotted against the percentage of pelvic muscular impairment or apical vaginal ligament impairment, and the plots were analyzed.

Chapter 4

Pelvic Floor Muscle Defect

4.1 The Role of Pelvic Floor Muscles in the Pelvic Support System and the Contribution of Their Weaknesses to the Development of Stress Urinary Incontinence

This chapter explains the research results that explicate the general role of pelvic floor muscles in the pelvic support system and the contribution of their weaknesses to the development of SUI in clinical patients. The role of pelvic floor muscles and the effect of pelvic muscle weakness on the pelvic support system were investigated through biomechanical model simulations of pelvic floor systems using patient-specific tissue parameters. The parameters were estimated based on clinical patient data, and they described the stiffness properties of vaginal and ligament tissues for individual patients. Using the mean values of the estimated vaginal and ligament parameters and the biomechanical model, the general role of pelvic floor muscles was assessed by simulating the behaviors of a pelvic support system with functional pelvic floor muscles (Module #1) and the behaviors of the pelvic support systems with impaired pelvic floor muscles (Module #3). On the other hand, using patient-specific material parameters and the model, the effect of pelvic muscle weakness on the pelvic floor support was assessed for individual clinical patients. Section 4.1.1 displays the estimated material parameters that described the stiffness properties of the vagina and apical vaginal ligaments for patients with pelvic floor muscle impairment. The section also discusses the statistical results that compare the mean material parameter values between patients with varied degree of

pelvic floor muscle impairments. Section 4.1.2 outlines and discusses the biomechanical modeling results that describe the general behavior of a pelvic support system with functional pelvic floor muscles and the general behavior of pelvic support systems with impaired pelvic floor muscles. Section 4.1.3 outlines the results that assessed the subsequent effect of varying the degree of pelvic floor muscle impairment on the bladder neck and apical vaginal support for specific patients who initially had 30% (Group 1A) or 60% (Group 1B) pelvic floor muscle impairment. Overall, the results summarized in the following sections describe the mechanisms of how pelvic musculature can impact pelvic floor support in healthy subjects and patients with pelvic floor disorders. The results are intended to illustrate the importance of pelvic floor musculature to the pelvic support system and to the maintenance of urinary continence.

4.1.1 Estimated material parameters

By implementing the clinical data of patients with primarily pelvic floor muscle impairment into the biomechanical model (Module #3), the parameters that describe the stiffness properties for the vaginal and apical vaginal ligament tissues ($C2_V$ and $C2_{AL}$) were determined for each patient with 30% pelvic floor muscle impairment (Group 1A), 60% pelvic floor muscle impairment (Group 1B), and 90% pelvic floor muscle impairments (Group 1C). The mean and the standard deviation (*SD*) values of the parameters for each patient group (Group 1A, 1B and 1C) are plotted in Figure 20. The mean and the standard deviation (*SD*) values of $C2_V$ for Groups 1A (sample size = 12), 1B (sample size = 11) and 1C (sample size = 3) are 8.32 (4.46), 13.71 (8.39), and 4.71 (2.14), respectively; the mean and the standard deviation values of $C2_{AL}$ for Group 1A, 1B and 1C are 2.48 (1.47), 3.32 (1.03), and 6.16 (3.13), respectively.

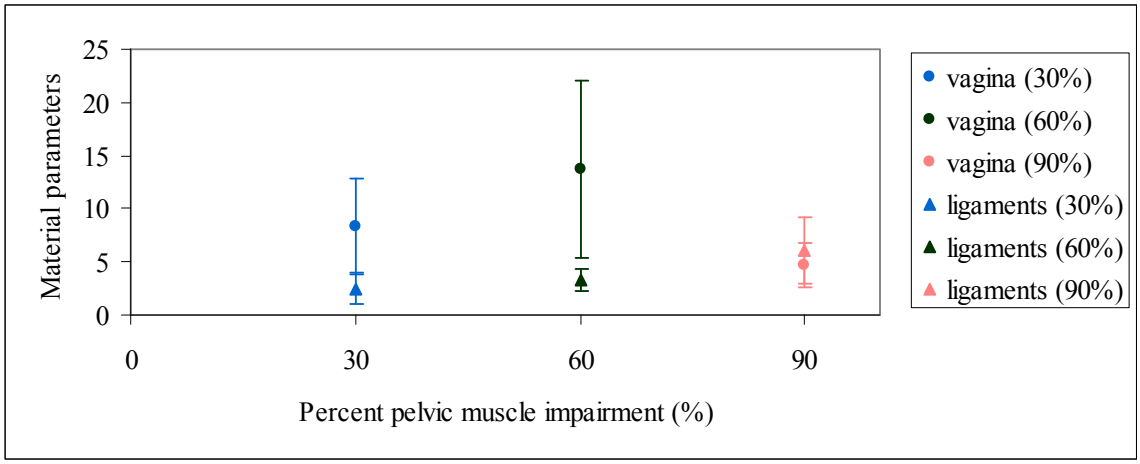

Figure 20 The material parameters of the vagina ($C2_V$) and apical vaginal ligaments ($C2_{AL}$) for patients with 30% (Group 1A), 60% (Group 1B) or 90% (Group 1C) pelvic muscle impairment.

Based on statistical Mann-Whitney *U* test, the $C2_V$ values of patients with 30% pelvic muscle impairment (Group 1A) and those of patients with 60% pelvic muscle impairment (Group 1B) did not demonstrate any statistical difference. This illustrate that the stiffness properties of the vaginal tissues exhibit no significant difference in patients with varied degree of pelvic floor muscle impairment. Alternatively, the $C2_{AL}$ values of patients with 60% pelvic muscle impairment (Group 1B) were demonstrated to be significantly higher than those of patients with 30% pelvic muscle impairment (Group 1A) ($P = 0.025$). The statistical results illustrate that the studied patients with more severe pelvic floor muscle impairment (Group 1B) have stiffer ligament tissues and that these tissues can increase their stiffness more sharply compared to those in patients with mild pelvic floor muscle impairment (Group 1A) when the tissues are strained. With severe pelvic floor muscle weaknesses, patients with ligament tissues that can increase their stiffness sharply in response to the increasing strain induced by increases in intra-abdominal loading may help to minimize the degree of pelvic organ prolapse. Nonetheless, due to the low sample size, the difference in pelvic tissue properties found in the studied patients may not be representative of the conditions generally found in the patient population with pelvic floor defects.

On the other hand, the vaginal and apical vaginal ligament parameters ($C2_V$ and $C2_{AL}$) were demonstrated to vary in patients with primarily pelvic floor muscle impairment (Group 1A, 1B and 1C) (Figure 20). This illustrates the variation of the material properties of pelvic tissues in individuals. For instance, patients with 30% pelvic floor muscle impairment (Group 1A) were demonstrated to have varied vaginal and ligament tissue parameters ($C2_V$ and $C2_{AL}$). In this group, some patients have high magnitude of vaginal and ligament tissue parameters. This implies that they have stiff vaginal and ligament tissues that can increase their stiffness sharply when they are strained. In a pelvic floor support system with weakened pelvic floor muscles, the vaginal and ligaments are exposed to additional intra-abdominal loading during a valsalva maneuver. Vaginal and ligament tissues that can increase their stiffness sharply in response to the increasing strain induced by increases in intra-abdominal loading may help to minimize the degree of pelvic floor prolapse. According to the clinical patient data, these patients were demonstrated to have minor elongation in their vaginal walls and ligaments during a valsalva maneuver, and this help to prevent severe prolapse of the bladder neck (points *Aa*) and vaginal apex (point *C* or *D*) positions. On the other hand, some patients with 30% pelvic floor muscle impairment have low magnitudes of vaginal and ligament tissue parameters. This implies that they have more elastic vaginal and ligament tissues that increase their stiffness gradually when they are strained. When the pelvic support system with weakened pelvic floor muscles is subjected to additional intra-abdominal loading, these vaginal and ligament tissues may not be able to increase their stiffness sharply to resist the straining, and this may lead to severe pelvic floor prolapse. According to the clinical data, these patients were demonstrated to have significant elongation in their vaginal and ligament tissues during a valsalva maneuver, and their elongation promote severely prolapsed bladder neck (points *Aa*) and vaginal apex (point *C* or *D*) positions (i.e. positive in magnitude). Patients with 60% (Group 1B) and 90% (Group 1C) pelvic floor muscle impairments were also shown to have varied vaginal and ligament parameters.

In pelvic system modeling, these varied tissue parameters can be used to model the diverse behaviors of the vaginal and ligament tissues under loading. Using a fixed set of tissue parameters, the model developed by Chen *et al*. (2006) have not shown the

diverse vaginal and ligament behaviors in pelvic support systems with weakened pelvic floor muscles under straining conditions. The model by Chen *et al*. (2006) only simulates the general vaginal wall behavior under straining conditions and demonstrates magnified prolapse in both distal and apical vaginal wall as the pelvic muscle impairment intensifies [109]. In contrast, the patient-specific tissues parameters obtained in the current study can be used in pelvic modeling to simulate the diverse pelvic support system behaviors for individual patients with primarily pelvic floor muscle impairment.

4.1.2 Modeling pelvic systems with functional or impaired pelvic floor muscles

The biomechanical model (Modules #1 and #2) developed in the current study was used to simulate the general behavior of a pelvic support system for a healthy subject with functional pelvic floor muscles during at rest condition and during a valsalva maneuver. Table 5 shows the force balance results computed by the model that describe the force equilibrium pelvic condition of a healthy subject during at rest and during a valsalva manuever. The purpose of performing the force balance is to demonstrate that during at rest and a valsalva maneuver, a normal pelvic support system is in equilibrium and that the pelvic floor muscles are involved in maintaining the equilibrium. As shown in Table 5, during at rest condition, the pelvic floor muscles exerted a resting muscle tone to help maintain equilibrium; on the other hand, during a valsalva maneuver, the pelvic floor muscles exerted an active muscle tone to help counteract the valsalva force (F_5).

Table 5 The force balance results for a healthy subject during at rest and on straining conditions

	F_1 (*N*)	F_3 (*N*)	F_4 (*N*)	F_5 (*N*)	F_{AS} (*N*)	Θ_1 (deg.)	Θ_3 (deg.)	Θ_5 (deg.)	Θ_{AS} (deg.)
Healthy subject									
At rest	2.2	2.7	1.0	0	4.6	48	28	-	78
During a valsalva	15.8	6.2	1.0	27.1	4.6	48	28	66.2	78

F_1,Θ_1: contractile force and inclination of iliococcygeus muscles; F_3,Θ_3: contractile force and inclination of pubococcygeus-puborectalis muscle; F_4: bladder weight; F_5,Θ_5: valsalva force and its inclination; F_{AS},Θ_{AS}: natural abdominal supporting force and its inclination.

In terms of pelvic support system behavior, the effect of functional pelvic floor muscles on the bladder neck and apical vaginal support during at rest and during a valsalva maneuver are simulated, and the modeled results are shown in Table 6. The modeled behaviors of a pelvic support system with functional pelvic floor muscles during at rest condition and during a valsalva maneuver are shown in Figures 6 and 8. According to Table 6 and Figures 6 and 8, when a pelvic support system with functional pelvic floor muscles is subjected to a valsalva pressure, the pelvic floor muscles contract fully, and the normal hiatus size is maintained. The pelvic support system remains in its equilibrium state, and no valsalva pressure is exerted onto the vagina and apical vaginal ligaments. The resulting bladder neck (point *Aa*) and vaginal apex (point *C*/*D*) locations remain the same as those during at rest condition. These results concur with the pelvic floor dynamics described by DeLancey *et al*. (1994) and Barber *et al*. (2005) [20, 39]. When additional intra-abdominal pressure is applied to the pelvic floor, normal pelvic musculature counters these forces by contracting. With full muscle tone, the stress acting on the vagina and connective ligaments is minimized. Thus, the bladder neck and vaginal apex locations remain the same as those at rest condition.

The biomechanical model (Module #3) was also used to simulate the general behaviors of the pelvic support systems for subjects with impaired pelvic floor muscles during a valsalva maneuver. The simulations assessed the general effect of impaired pelvic floor muscles on the bladder neck and apical vaginal support in a pelvic support system. The modeled results for subjects with 30%, 60% or 90% pelvic floor muscle impairment are shown in Table 6. The modeled behaviors of a pelvic support system with functional pelvic floor muscles during at rest condition and during a valsalva maneuver are shown in Figure 10. According to the modeled results, when a pelvic support system with impaired pelvic floor muscles is subjected to valsalva pressure, the muscles cannot contract fully to counteract the pressure and maintain the normal hiatus size. The hiatus then widens, allowing the valsalva pressure to act on the distal portion of the vagina and eventually on the apical vaginal ligaments. The pressure strained the vagina and apical vaginal ligaments, causing the bladder neck (points *Aa*) and vaginal apex (point *C* or *D*) to prolapse caudally. According to Table 6, the degree of bladder neck and vaginal apex prolapse is shown to intensify as the percent of pelvic muscle

impairment increases. These results are in contrast with those observed in the normal pelvic support system, and they illustrate the importance of normal pelvic floor muscles to both bladder neck and vaginal apex support. The results concur with the pelvic floor dynamics described by Barber et al. (2005) [20]. During straining conditions, impaired pelvic muscles lose the normal tone to resist the increases in intra-abdominal pressure. The vaginal tissues and connective ligaments then become the primary mechanism of support. These connective structures become stretched, leading to prolapse of the bladder neck and vaginal apex.

Table 6 Modeled results for a subject with healthy pelvic floor muscles during at rest and a valsalva maneuver and 3 subjects with impaired pelvic floor muscles during a valsalva maneuver.

	Percent muscle defect (%)	**F_3(*N*)**	**l_{PPM} (*cm*)**	**Θ_S (degree)**	**Point *Aa* (at rest, on strain) (*cm*)**	**Point *C* or *D* (at rest, on strain) (*cm*)**
Healthy subject						
At rest	0	2.7	8.7	0	-3, -3	-9, -9
During a valsalva	0	6.2	8.7	0	-3, -3	-9, -9
Subjects with pelvic disorders						
1	30	4.3	10.3	10.7	-3, -0.3	-9, -7.3
2	60	2.5	11.6	19.3	-3, 0.4	-9, -6.8
3	90	0.6	13.7	33.4	-3, 1.4	-9, -6.0

F_3: muscle contractile force; l_{PPM}: final length of puborectalis-pubococcygeus muscle; Θ_S: angular change in the orientation of the iliococcygeus muscles; point *Aa*: distance of bladder neck location relative to vaginal introitus; point *C* or *D*: distance of vaginal apex relative to vaginal introitus.

4.1.3 The impact of pelvic muscle defect on the bladder neck and apical vaginal support

By using the developed biomechanical model with the estimated patient-specific material parameters, and varying the percentage of the pelvic muscle impairment, the changes in the bladder neck (point *Aa*) and vaginal apex (point *C* or *D*) positions relative to the vaginal introitus were assessed for individual patients who initially had 30% (Group 1A) and 60% (Group 1B) muscle impairments.

For patients who initially present with 30% pelvic muscle impairment (Group 1A), the mean and the standard deviation (*SD*) values of the initial points *Aa* and points *C*

or *D* at 30% pelvic muscle impairment, and those of the assessed points *Aa* and points *C* or *D* at 60% and 90% pelvic muscle impairments are plotted in Figure 21. According to Figure 21, both points *Aa* and points *C* or *D* prolapse caudally (i.e. becomes more positive in magnitude) as the percent pelvic muscle impairment increases (i.e. from 30% to 60% and 90% pelvic muscle impairment). This suggests that impaired pelvic floor muscles can directly weaken both bladder neck and vaginal apex support. The estimated magnitudes of POPQ points at 60% and 90% pelvic muscle impairments shown in Figure 21 were dependent on the individual's initial vaginal prolapse condition at 30% pelvic muscle impairment. For instance, patients with initially severe vaginal prolapse (i.e. more positive points *Aa* and points *C* or *D*) were estimated to have high magnitudes of POPQ points (i.e. points *Aa* and points *C* or *D* approaching +3 *cm* and + total vaginal length, respectively) as the percent of pelvic muscle impairment intensified. On the other hand, those with initially mild vaginal prolapse (i.e. more negative points *Aa* and points *C* or *D*) were estimated to have low magnitudes of POPQ points as the percent pelvic muscle impairment intensified.

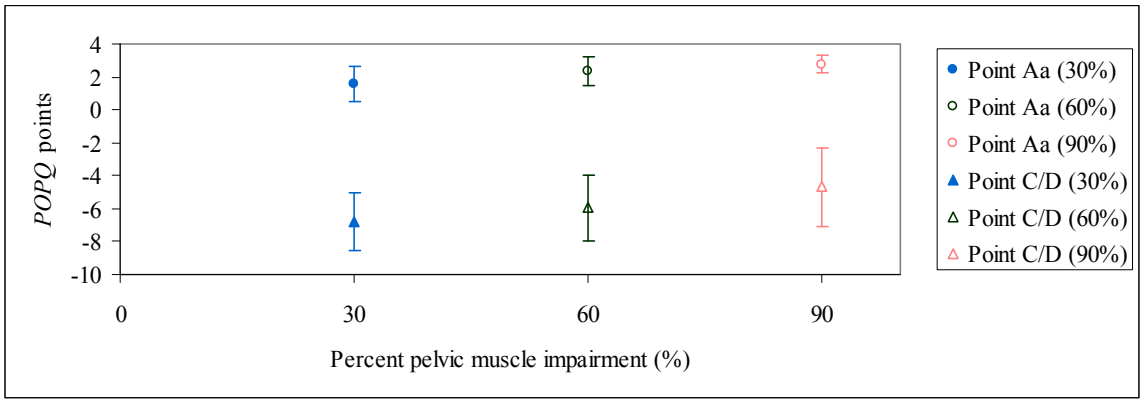

Figure 21 The bladder neck positions (points *Aa*) and vaginal apex positions (points *C* or *D*) at 60% and 90% pelvic muscle impairment assessed for patients who initially had 30% pelvic muscle impairment. The mean values of the initial points *Aa* and *C* or *D* at 30% pelvic muscle impairment (Group 1A) are denoted by (●) and (▲), respectively. The mean values of the assessed points *Aa* and *C* or *D* at 60% and 90% pelvic muscle impairments are denoted by (○) and (Δ), respectively.

For patients who initially present with 60% pelvic muscle impairment (Group 1B), the mean and the standard deviation (*SD*) values of the initial points *Aa* and *C* or *D* at 60%

pelvic muscle impairment, and those of the assessed points *Aa* and points *C* or *D* at 30% and 90% pelvic muscle impairments are plotted in Figure 22. According to Figure 22, points *Aa* and *C* or *D* approach normal positions (i.e. becomes more negative in magnitude) as the percent pelvic muscle impairment decreases (i.e. from 60% to 30% pelvic muscle impairment). This suggests that rehabilitated pelvic floor muscles can help re-establish both bladder neck and vaginal apex support for patients with primarily pelvic floor muscle impairment. Alternatively, these POPQ points prolapse caudally as the percent muscle impairment increases (i.e. from 60% to 90% pelvic muscle impairment). This suggests that impaired pelvic floor muscles can directly weaken both bladder neck and vaginal apex support for patients with primarily pelvic floor impairment. The estimated magnitudes of POPQ points at 30% and 90% pelvic muscle impairments shown in Figure 22 were dependent on the individual's initial vaginal prolapse condition at 60% pelvic muscle impairment. For instance, patients with initially severe vaginal prolapse (i.e. more positive points *Aa* and points *C* or *D*) were estimated to have high magnitudes of POPQ points (i.e. points *Aa* and points *C* or *D* approaching +3 *cm* and + total vaginal length, respectively) as the pelvic muscle impairment intensified (i.e. from 60% to 90% muscle impairment), and they were estimated to have POPQ points that deviated greatly from the normal positions (i.e. normal positions of points *Aa* and points *C* or *D* are respectively –3 *cm* and –vaginal length in *cm*) as the pelvic muscle impairment decreased. On the other hand, patients with initially mild vaginal prolapse (i.e. more negative points *Aa* and points *C* or *D*) were estimated to have low magnitudes of POPQ points as the pelvic muscle impairment increased, and they were estimated to have POPQ points that advanced more closely to normal positions (points *Aa* approaching –3 *cm* and points *C* or *D* approaching -vaginal length in *cm*) as the pelvic muscle impairment decreased.

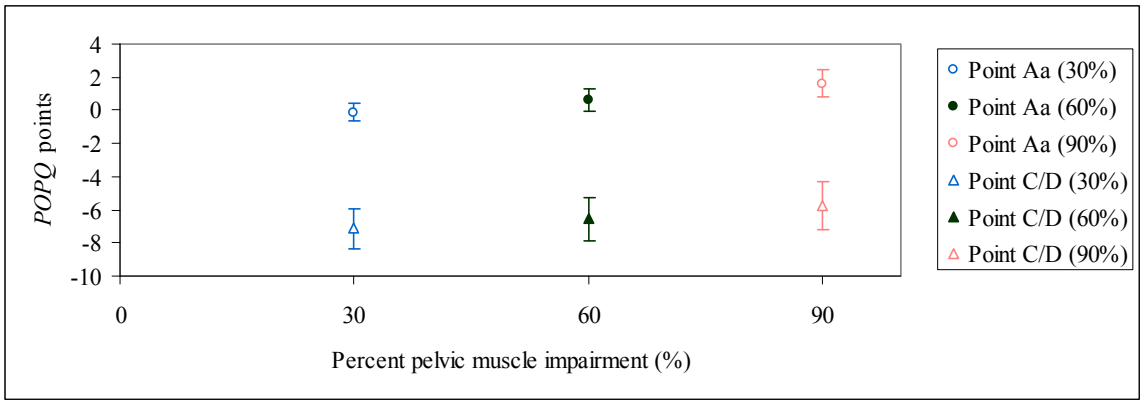

Figure 22 The bladder neck positions (points *Aa*) and vaginal apex positions (points *C* or *D*) at 30% and 90% pelvic muscle impairment assessed for patients who initially had 60% pelvic muscle impairment. The mean values of the initial points *Aa* and *C* or *D* at 60% pelvic muscle impairment (Group 1B) are denoted by (●) and (▲), respectively. The mean values of the assessed points *Aa* and *C* or *D* at 30% and 90% pelvic muscle impairments are denoted by (○) and (Δ), respectively.

The modeling results outlined in the current section are consistent with the clinical condition of pelvic organ prolapse, and they demonstrate the significance of pelvic muscle strength to both bladder neck and apical vaginal support with increases in intra-abdominal pressure. The results are clinically useful, since they not only postulate the amount of muscle tone that is required to improve the bladder neck and apical vaginal support for individual patients, but they also predict the prolapsed conditions that can result when the muscle tone is reduced.

Chapter 5

Cardinal and Uterosacral Ligament Defect

5.1 The Role of Cardinal and Uterosacral Ligaments in the Pelvic Support System and the Contribution of Their Weaknesses to the Development of Stress Urinary Incontinence

This chapter exemplifies the research results that explain general role of cardinal and uterosacral ligaments in the pelvic support system and the contribution of their weaknesses to the development of SUI in clinical patients. The role of cardinal and uterosacral ligaments and the effect of pelvic ligament weakness on the pelvic floor support were investigated through biomechanical model simulations of pelvic floor systems using patient-specific tissue parameters. The parameters were estimated based on clinical patient data, and they described the stiffness properties of vaginal and ligament tissues for individual patients. Using the mean values of the estimated vaginal and ligament parameters and the biomechanical model, the general role of cardinal and uterosacral ligaments was assessed by simulating the behaviors of a pelvic support system with functional apical vaginal ligaments (Module #1) and the behaviors of the pelvic support systems with impaired apical vaginal ligaments (Module #4). On the other hand, using patient-specific material parameters and the model, the effect of cardinal and uterosacral ligament weakness on the pelvic floor support was assessed for individual clinical patients. Section 5.1.1 displays the estimated material parameters that described the stiffness properties of the vagina and apical vaginal ligaments for patients with primarily cardinal and uterosacral ligament (i.e. apical vaginal ligaments) impairment

(Group 2) and for patients with both cardinal and uterosacral ligament impairment and pelvic floor muscle impairment (Group 3). The section also discusses the statistical results that compare the mean parameter values between patients with apical vaginal ligament impairment and varied degree of coexisting pelvic floor muscle impairment. Section 5.1.2 outlines and discusses the biomechanical modeling results that describe the general behavior of a pelvic support system with functional apical vaginal ligaments and the general behavior of pelvic support systems with impaired apical vaginal ligaments. Section 5.1.3 outlines the modeling results that assessed the subsequent effect of varying the degree of apical vaginal ligament impairment on the bladder neck and apical vaginal support for specific patients who had apical vaginal ligament impairment and/ or coexisting pelvic floor muscle impairment. Overall, the results summarized in the following sections describe the mechanisms of how apical vaginal ligaments can impact pelvic floor support in healthy subjects and patients with pelvic floor disorders. The results are intended to illustrate the importance of cardinal and uterosacral ligaments to the pelvic support system and to the maintenance of urinary continence.

5.1.1 Estimated material parameters

By implementing the clinical data of patients with apical vaginal ligament impairment into the biomechanical model (Modules #4 and #5), the parameters that describe the stiffness properties for the vaginal ($C2_V$) and apical vaginal ligament ($C2_{AL}$) tissues were determined for each patient with primarily apical vaginal ligament impairment (Group 2) and for each patient with both apical vaginal ligament impairment and 30% pelvic floor muscle impairment (Group 3A), 60% pelvic floor muscle impairment (Group 3B) or 90% pelvic floor muscle impairments (Group 3 C). The mean and the standard deviation (*SD*) values of $C2_V$ and $C2_{AL}$ for patients in Group 2 (sample size = 5) are 4.72 (3.11) and 2.59 (2.00), respectively. The mean and the standard deviation (*SD*) values of $C2_V$ for patients in Groups 3A (sample size = 12), 3B (sample size = 11) and 3C (sample size = 3) are the same as those in Group 1A, 1B and 1C, and they are 8.32 (4.46), 13.71 (8.39), and 4.71 (2.14), respectively; the mean and the

standard deviation (*SD*) values of $C2_{AL}$ for patients in Groups 3A, 3B and 3C are 2.72 (1.46), 3.61 (1.03), and 6.53 (3.08), respectively.

Statistical tests were performed to compare the material parameters ($C2_V$ and $C2_{AL}$) between Group 2, Group 3A, and Group 3B patients. The material parameters of Group 2 and Group 3 patients were then plotted against the percent of pelvic ligament and muscle impairment. By analyzing the statistical and graphical results, the difference in the mechanical properties of the vaginal and ligament tissues of Group 2 and Group 3 patients are evaluated.

Based on Mann Whitney *U*-test, the values of the vaginal ($C2_V$) and ligament ($C2_{AL}$) parameters for patients with apical vaginal ligament impairment and 30% coexisting pelvic floor muscle impairment (Group 3A) did not demonstrate significant difference when compared to the values of patients with primarily apical vaginal ligament impairment (Group 2). However, the values of the vaginal ($C2_V$) and ligament ($C2_{AL}$) parameters for patients with apical vaginal ligament impairment and 60% coexisting pelvic floor muscle impairment (Group 3B) were found to be significantly higher when compared to those of the patients with primarily apical vaginal ligaments (Group 2) ($P < 0.05$). Table 7 displays the results for the statistical tests. The statistical results imply that the studied patients with both apical vaginal ligament and 60% pelvic floor muscle impairment (Group 2B) have stiffer vaginal and ligament tissues, and that these tissues can increase their stiffness more sharply compared to those in patients with primarily apical vaginal ligament impairment when they are strained. With both apical vaginal ligament and severe pelvic floor muscle weaknesses, patients with pelvic tissues that can increase their stiffness sharply in response to the increasing strain induced by the increases in intra-abdominal pressure may help to minimize the severity of pelvic organ prolapse. Nonetheless, due to the low sample size, the difference in pelvic tissue properties found in the studied patients may not be representative of the conditions generally found in the patient population with pelvic floor defects.

Table 7 Statistical test results that compare the material parameters of the vagina and ligaments between patients with primarily apical vaginal ligament impairment (Group 2) and patients with apical vaginal ligament impairment and 30% (Group 3A), 60% (Group 3B) or 90% (Group 3C) coexisting pelvic muscle impairment.

Statistical Tests	Patient Groups	Sample size (Group no. = number)	Mean values (Deviation)	*P* values
Stiffness parameters for vagina ($C2_V$)				
2-sample Mann-Whitney *U* test (1 tail)	3A > 2	2 = 5, 3A = 12	2: 4.72 (3.11), 3A: 8.32 (4.46)	> 0.05
2-sample Mann-Whitney *U* test (1 tail)	3B > 2	2 =5 , 3B = 11	2: 4.72 (3.11), 3B: 13.71 (8.39)	< 0.025
Stiffness parameters for ligaments ($C2_{AL}$)				
2-sample Mann-Whitney *U* test (1 tail)	3A > 2	2 = 5, 3A = 12	2: 2.59 (2.00), 3A: 2.72 (1.46)	> 0.05
2-sample Mann-Whitney *U* test (1 tail)	3B > 2	2 =5 , 3B = 11	2: 2.59 (2.00), 3B: 3.61 (1.03),	< 0.05

In terms of graphical plots, the material parameters of the vagina ($C2_V$) and apical vaginal ligaments ($C2_{AL}$) for patients with apical vaginal ligament impairment and varied degree of pelvic floor muscle impairment were plotted against the percentage of apical vaginal ligament impairment and the percentage of pelvic floor muscle impairment as shown in Figures 23 and 24, respectively. Figure 23 shows a plot of the material parameters of the vagina ($C2_V$) versus the percentage of apical vaginal ligament impairment for patients with apical vaginal ligament impairment and 0% pelvic floor muscle impairment (Group 2), 30% pelvic floor muscle impairment (Group 3A), 60% pelvic floor muscle impairment (Group 3B) or 90% pelvic floor muscle impairment (Group 3C). According to Figure 23, the magnitudes of the vaginal parameters ($C2_V$) for all four groups of patients were demonstrated to have no apparent relationship with the degree of apical vaginal ligament impairment. This suggests that the stiffness properties of the vaginal tissues in the studied patients are not influenced by the material properties of the apical vaginal ligament tissues. Moreover, as shown in Figure 23, the vaginal parameters were demonstrated to vary between patients. This illustrates the variation of the material properties of pelvic tissues in individuals. For instance, patients with the same degree apical vaginal ligament and pelvic floor muscle impairment were

demonstrated to have varied vaginal tissue parameters ($C2_V$). Some patients have high magnitude of vaginal parameters. This implies that they have stiff vaginal tissues that can increase their stiffness sharply when they are strained. In a pelvic floor support system with weakened apical vaginal ligaments and pelvic floor muscles, the vaginal tissues are exposed to pressure during straining conditions. Vaginal tissues that can increase their stiffness sharply in response to the increasing strain caused by increases in intra-abdominal loading may help to minimize the degree of pelvic floor prolapse. According to the clinical patient data, these patients were demonstrated to have minor elongation in their vaginal walls, and this help to prevent severe prolapse of their bladder neck (points *Aa*) positions during a valsalva maneuver. On the other hand, some patients have low magnitudes of vaginal parameters. This implies that they have more elastic vaginal tissues that increase their stiffness gradually when they are strained. When the pelvic support system with weakened apical vaginal ligaments and pelvic floor muscles is subjected to additional intra-abdominal loading during a valsalva maneuver, these vaginal tissues may not be able to increase their stiffness sharply to resist the straining, and this may lead to severe pelvic floor prolapse. According to the clinical patient data, these patients were demonstrated to have significant elongation in their vaginal walls, and their elongation promote severely prolapsed bladder neck (points *Aa*) positions (i.e. positive in magnitude) during a valsalva maneuver.

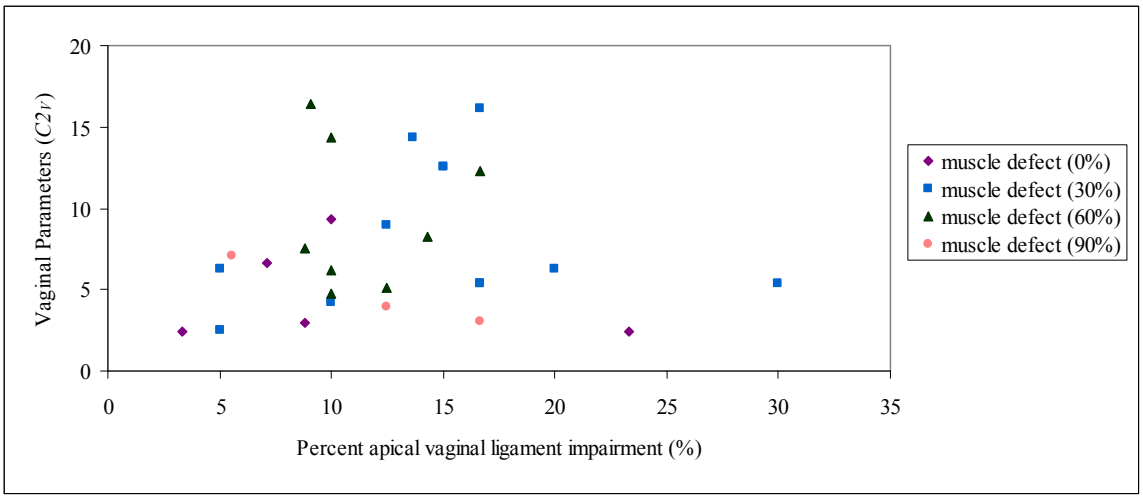

Figure 23 The material parameters of the vagina ($C2_V$) for patients with primarily apical vaginal ligament impairment (Group 2) and patients with apical vaginal ligament impairment and 30% (Group 3A), 60% (Group 3B) or 90% (Group 3C) coexisting pelvic floor muscle impairment.

Figure 24 shows a plot of the material parameters of the apical vaginal ligaments ($C2_{AL}$) versus the percentage of pelvic floor muscle impairment for patients with apical vaginal ligament impairment and 0% (Group 2), 30% (Group 3A), 60% (Group 3B) or 90% pelvic floor muscle impairment (Group 3C). According to Figure 24, patients with apical vaginal ligament impairment and severe pelvic floor muscle impairment (60% and 90%) were shown to have higher ligament parameters compared to those of patients with apical vaginal ligament impairment and mild pelvic floor muscle impairment (0% and 30%). This illustrate that the studied patients with impaired ligaments and severe pelvic muscle impairment have stiffer ligament tissues, and that these tissues can increase their stiffness more sharply compared to those in patients with ligament impairment and mild pelvic floor muscle impairment when the tissues are strained. With impaired apical vaginal ligaments and severe pelvic muscle weakness, patients who have apical vaginal ligaments that can increase their stiffness sharply in response to the increasing strain induced by increases in the intra-abdominal loading may help to minimize the degree of pelvic organ prolapse. Yet, due to the low sample size, the difference in pelvic tissue properties observed in the current studied patients may not be representative of the conditions generally found in the patient population with pelvic floor defects.

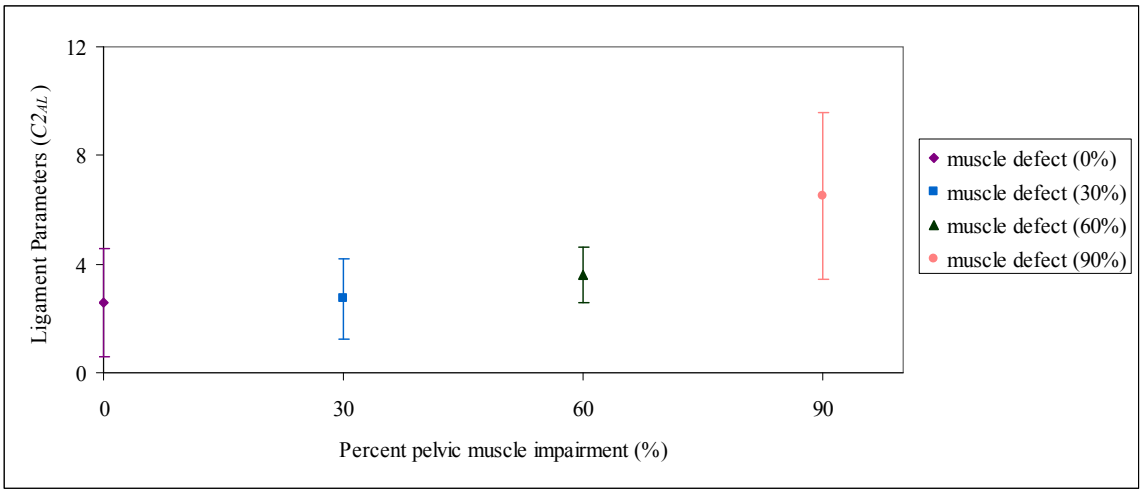

Figure 24 The material parameters of the apical vaginal ligaments ($C2_{AL}$) for patients with primarily apical vaginal ligament impairment (Group 2) and patients with apical vaginal ligament impairment and 30% (Group 3A), 60% (Group 3B) or 90% (Group 3C) coexisting pelvic floor muscle impairment.

In the current study, the tissue parameters estimated for the clinical patients illustrate the diverse vaginal and ligament tissue properties found in females. These patient-specific parameters can be used in pelvic modeling to simulate the diverse pelvic system behaviors for individual patients with apical vaginal ligament impairment and pelvic floor muscle impairments.

5.1.2 Modeling pelvic systems with functional or impaired cardinal and uterosacral ligaments

The biomechanical model (Modules #1 and #2) developed in the current study was used to simulate the general behavior of a pelvic support system for a healthy subject with functional cardinal and uterosacral ligaments during at rest condition and during a valsalva maneuver. The simulations assess the general effect of functional cardinal and uterosacral ligaments on the bladder neck and apical vaginal support during at rest condition and under a valsalva maneuver, and the modeled results are shown in Table 8. The modeled behaviors of a pelvic support system with functional cardinal and uterosacral ligaments during at rest condition and under a valsalva maneuver are shown in Figures 6 and 8. According to Table 8 and Figures 6 and 8, when a normal pelvic support system is subjected to a valsalva pressure, the pelvic floor muscles contract fully. At the same time, the apical vaginal ligaments (cardinal and uterosacral ligaments) remain taut. The pelvic support system remains in equilibrium state, and no valsalva pressure is exerted onto the vaginal and the apical vaginal ligaments. Thus, the resulting bladder neck (point *Aa*) and the vaginal apex (point *C*/*D*) locations remain the same as those during at rest condition. These results concur with the pelvic floor dynamics described by Barber et al. (2005) and Petros et al. (1990 and 2007) [18, 20, 90]. When additional intra-abdominal pressure is applied to the pelvic floor, normal pelvic musculature counters the pressure by contracting. With full muscle tone, the stress acting on the vagina and connective ligaments is minimized. Concurrently, the cardinal and uterosacral ligaments remain stiff to promote tightening of the vagina and maintain upper vaginal support. Thus, the bladder neck and vaginal apex locations remain the same as those during at rest condition.

Table 8 Modeled results for a subject with functional cardinal and uterosacral ligaments and pelvic floor muscles during at rest and on straining condition, and 8 subjects with impaired apical vaginal ligaments and or coexisting pelvic floor muscle impairment during on straining condition.

	Percent muscle defect (%)	Percent ligament defect (%)	$F_3(N)$	l_{PPM} (cm)	Θ_S (degree)	Point Aa (at rest, on strain) (cm)	Point C or D (at rest, on strain) (cm)
Healthy subject							
1 At rest	0	0	2.7	8.7	0	-3, -3	-9, -9
1 On strain	0	0	6.2	8.7	0	-3, -3	-9, -9
Subjects with pelvic disorders							
2	0	40	6.2	8.7	0	-3, -0.8	-9, -7.7
3	0	60	6.2	8.7	0	-3, -0.3	-9, -7.2
4	30	40	4.3	10.3	10.7	-3, -0.4	-9, -7.1
5	30	60	4.3	10.3	10.7	-3, 1.1	-9, -6.0
6	60	40	2.5	11.6	19.3	-3, 1.2	-9, -6.1
7	60	60	2.5	11.6	19.3	-3, 1.9	-9, -5.4
8	90	20	0.6	13.7	33.4	-3, 1.8	-9, -5.7
9	90	40	0.6	13.7	33.4	-3, 2.3	-9, -5.2

F_3: muscle contractile force; l_{PPM}: final length of puborectalis-pubococcygeus muscle; Θ_S: change in the orientation of the iliococcygeus muscles; point Aa: distance of bladder neck location relative to vaginal introitus; point C or D: distance of vaginal apex relative to vaginal introitus.

The biomechanical model (Modules #4 and #5) was also used to simulate the general behaviors of the pelvic support systems for subjects with impaired cardinal and uterosacral ligaments and/ or coexisting impaired pelvic floor muscles. The simulations assess the general effect of impaired cardinal and uterosacral ligaments on the bladder neck and apical vaginal support during a valsalva maneuver. The modeled results for eight subjects with varied percentage of apical vaginal ligament impairment during a valsalva maneuver are shown in Table 8. Six of the eight subjects shown in Table 8 have coexisting pelvic muscle impairment. The general modeled behavior of an abnormal pelvic support system with primarily apical vaginal ligament impairment during a valsalva maneuver is shown in Figure 16. The general modeled behavior of an abnormal pelvic support system with impaired apical vaginal ligaments and impaired pelvic floor muscles during a valsalva maneuver is shown in Figure 10. According to Table 8 and

Figure 16, when the pelvic support system with impaired apical vaginal ligaments is subjected to valsalva pressure, and the pelvic floor muscles are not contracted simultaneously when the pressure is exerted, both the vaginal wall and the impaired apical vaginal ligaments are exposed to and strained by the pressure. As the vaginal wall and impaired ligaments are stretched, the bladder neck (points *Aa*) and vaginal apex (points *C* or *D*) prolapse caudally. As shown in Table 8, the degree of bladder neck and vaginal apex prolapse is demonstrated to intensify as the percentage of apical vaginal ligament impairment increases. On the other hand, according to Table 8 and Figure 10, when the pelvic support system with impaired apical vaginal ligaments and pelvic floor muscles is subjected to valsalva pressure during a valsalva maneuver, the impaired pelvic floor muscles cannot contract fully to counteract the pressure and maintain the normal hiatus size. The hiatus then widens, allowing the valsalva pressure to act on the distal portion of the vagina and eventually on the apical vaginal ligaments. The pressure strained the vagina and the impaired apical vaginal ligaments, causing the bladder neck (points *Aa*) and vaginal apex (point *C* or *D*) to prolapse caudally. According to Table 8, the degree of bladder neck and vaginal apex prolapse in subjects with both apical vaginal ligament impairment and pelvic muscle impairment are shown to be greater when compared to those of the subjects with primarily pelvic floor muscle impairment (Table 6). These results are in contrast with those observed in the normal pelvic support system, and they illustrate the importance of normal pelvic cardinal and uterosacral ligaments to both bladder neck and vaginal apex support. The results concur with the pelvic floor dynamics described by Barber *et al*. (2005), Summer *et al*. (2006) and Petros *et al*. (1990 and 2007) [18, 20, 22, 90]. Patients with primarily apical vaginal ligament impairment have defective apical vaginal support, which promote loosening of the vaginal wall. During straining conditions, increases in intra-abdominal pressure can cause prolapse of the vaginal apex and bladder neck. On the other hand, patients with coexisting pelvic floor muscle impairment have primary muscular support that lacks the normal tone to resist the increases in intra-abdominal loading during straining conditions. The vaginal tissues and impaired connective ligaments then become the primary mechanism of support. These connective structures become stretched, leading to prolapse of the vaginal apex and bladder neck.

5.1.3 The impact of apical vaginal ligament defect on the bladder neck and apical vaginal support

By using the developed biomechanical model (Modules #4 and #5) with the estimated patient-specific material parameters, and varying the percentage of the apical vaginal ligament impairment, the changes in the bladder neck (point *Aa*) and vaginal apex (point *C* or *D*) positions relative to the vaginal introitus were evaluated for individual patients who had primarily apical vaginal ligament impairment (Group 2) and for patients who had both apical vaginal ligament and pelvic floor muscle impairments (Group 3).

For patients with primarily apical vaginal impairment (Group 2), the mean and the standard deviation (*SD*) values of the assessed bladder neck locations (points *Aa*) relative to the vaginal introitus at 0%, 20%, 40%, 60%, 80% and 100% apical vaginal ligament impairments are shown in Figure 25.

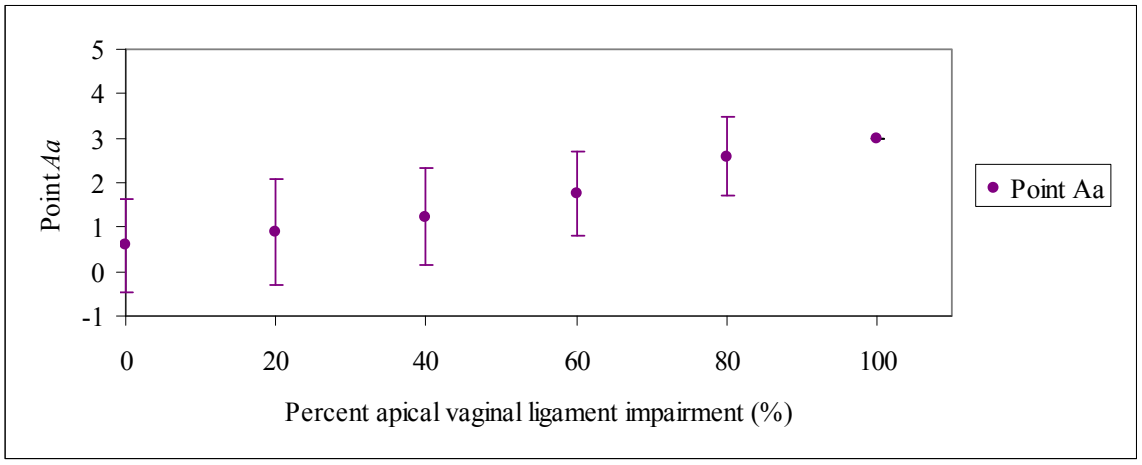

Figure 25 The bladder neck positions (points *Aa*) at 0%, 20%, 40%, 60%, 80% and 100% apical vaginal ligament impairment assessed for patients with primarily apical vaginal ligament impairment (Group 2).

According to Figure 25, points *Aa* prolapse caudally (i.e. becomes more positive in magnitude) as the percent apical vaginal ligament impairment increases (i.e. increases to 100% ligament impairment). This suggests that impaired apical vaginal ligaments can directly weaken bladder neck support. Conversely, points *Aa* approach to normal positions (i.e. become more negative in magnitude) as the percent apical vaginal ligament

impairment decreases (i.e. decreases to 0% ligament impairment). This suggests that reconditioned apical vaginal ligaments can help re-establish bladder neck support for patients with primarily apical vaginal ligament impairment. As shown in the figure, point *Aa* can only be re-established to a mean position of 0.59 *cm* (*SD*: 1.06 *cm*) when conditions of completely restored ligaments were simulated, since the current model is built based on the presumption that these patients have delayed pelvic floor muscle contraction at the time when valsalva pressure, generated during a valsalva maneuver, is applied onto the pelvic floor. As a result, even with strong apical vaginal support, the distal vaginal wall is still exposed to the valsalva pressure, and this eventually leads to bladder neck prolapse. The results illustrate the importance of well-timed pelvic muscle use, a technique also known as knack [41, 119]. For patients with urinary incontinence, it is crucial that they are trained to squeeze their pelvic muscles in times of strenuous activities to promote bladder neck support and to prevent urine leakage. Moreover, the estimated bladder neck locations at varied percentage of apical vaginal ligament impairments (i.e. 0%, 20%, 40%, 60%, 80% and 100%) were found to be dependent on the individual's initial bladder neck prolapse condition. For instance, patients with initially severe bladder neck prolapse (i.e. more positive points *Aa*) were estimated to have high magnitudes of point *Aa* (i.e. points *Aa* approaching +3 *cm*) as the apical vaginal ligament impairment intensified (i.e. increase to 100% apical vaginal ligament impairment). On the other hand, patients with initially mild bladder neck prolapse (i.e more negative points *Aa*) were estimated to have low magnitudes of point *Aa* as the apical vaginal impairment intensified (i.e. increase to 100% ligament impairment).

For patients with apical vaginal ligament impairment and pelvic floor muscle impairment (Groups 3A and 3B), the mean and the standard deviation (*SD*) values of the assessed bladder neck locations (point *Aa*) relative to the vaginal introitus at 0%, 20%, 40%, 60%, 80% and 100% apical vaginal ligament impairments are plotted in Figures 26 and 27. Figure 26 shows the assessed locations of point *Aa* for patients with apical vaginal ligament impairment and 30% coexisting pelvic floor muscle impairment (Group 3A). Figure 27, on the other hand, shows the assessed locations of point *Aa* for patients with apical vaginal ligament impairment and 60% coexisting pelvic floor muscle impairment (Group 3B).

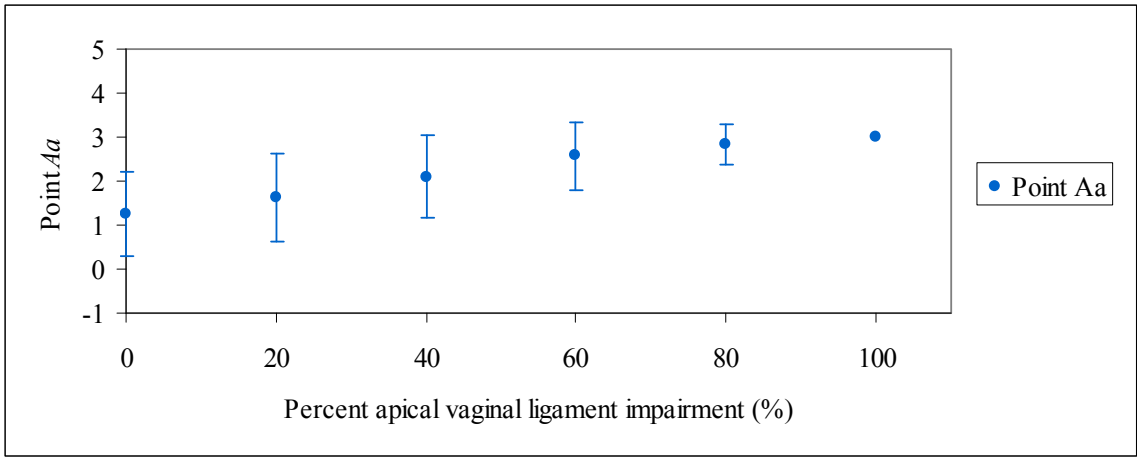

Figure 26 The bladder neck positions (points *Aa*) at 0%, 20%, 40%, 60%, 80% and 100% apical vaginal ligament impairment assessed for patients with apical vaginal ligament impairment and 30% coexisting pelvic floor muscle impairment (Group 3A).

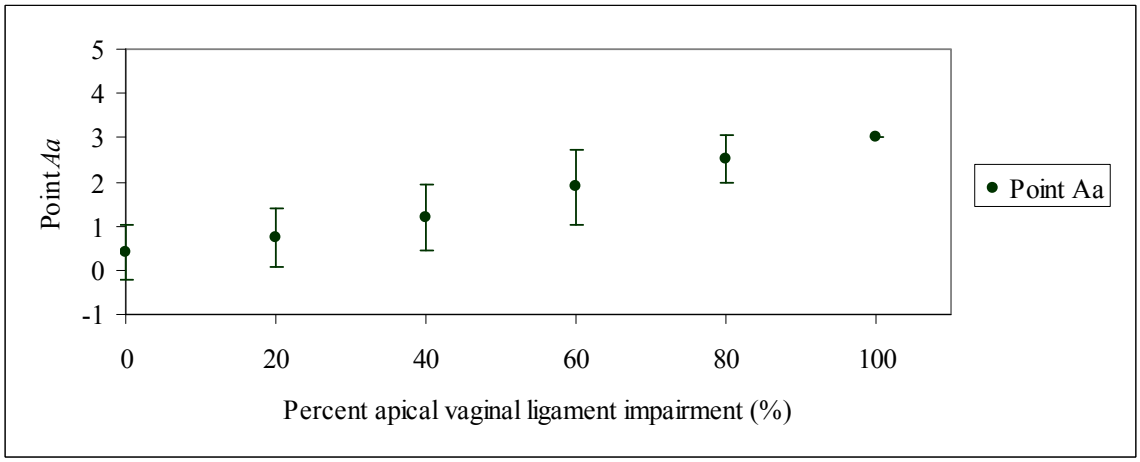

Figure 27 The bladder neck positions (points *Aa*) at 0%, 20%, 40%, 60%, 80% and 100% apical vaginal ligament impairment assessed for patients with apical vaginal ligament impairment and 60% coexisting pelvic floor muscle impairment (Group 3B).

According to Figures 26 and 27, points *Aa* prolapse caudally (i.e. become more positive in magnitude) as the percent ligament impairment increases (i.e. increases to 100% lament impairment). This suggests that impaired apical vaginal ligaments can directly weaken bladder neck support. Conversely, points *Aa* approach normal positions (i.e. become more negative in magnitude) as the percent apical vaginal ligament impairment

decreases. This suggests that reconditioned apical vaginal ligaments can help re-establish bladder neck supports for patients with both apical vaginal ligament impairment and pelvic muscle impairment. However, the bladder neck supports cannot be fully re-established if only the apical vaginal ligaments are reconditioned. According to Figures 26 and 27, patients with 30% and 60% coexisting pelvic muscle impairment were estimated to have their bladder neck supports (points *Aa*) re-established to a mean position of only 1.25 *cm* (*SD*: 0.98 *cm*) and 0.41 *cm* (*SD*: 0.62 *cm*), respectively, relative to the introitus, when conditions of completely restored apical vaginal supports were simulated. These findings illustrate the inadequacies of vaginal apex rehabilitation in restoring the bladder neck supports for patients with both apical vaginal ligaments and pelvic floor muscular deficiency. The results emphasize the need to rehabilitate the coexisting impaired pelvic floor muscles, in addition to the vaginal apex rehabilitation, in order to fully re-establish the bladder neck supports for these patients. Furthermore, the estimated bladder neck locations (point *Aa*) at varied percentage of apical vaginal ligament impairments (i.e. 0%, 20%, 40%, 60%, 80% and 100%) were found to be dependent on the individual's initial bladder neck prolapse condition. For instance, patients with initially severe bladder neck prolapse (i.e. more positive points *Aa*) were estimated to have high magnitudes of point *Aa* (i.e. points *Aa* approaching +3 *cm*) as the apical vaginal ligament impairment intensified (i.e. increase to 100% apical vaginal ligament impairment). On the other hand, patients with initially mild bladder neck prolapse (i.e more negative points *Aa*) were estimated to have low magnitudes of point *Aa* as the apical vaginal impairment intensified (i.e. increase to 100% apical vaginal ligament impairment).

In terms of the vaginal apex locations, Figures 28 to 30 show the mean and the standard deviation (*SD*) values of the assessed vaginal apex locations (point *C* or *D*) at 0%, 20%, 40%, 60%, 80% and 100% apical vaginal ligament impairments for patients with apical vaginal ligament impairment and varied degree of pelvic floor muscle impairment. Figure 28 shows the assessed points *C* or *D* for patients with primarily apical vaginal ligament impairment (Group 2). Figure 29 shows the assessed points *C* or *D* for patients with apical vaginal ligament impairment and 30% coexisting pelvic floor muscle impairment (Group 3A). Figure 30 shows the assessed points *C* or *D* for patients with

apical vaginal ligament impairment and 60% coexisting pelvic floor muscle impairment (Group 3B).

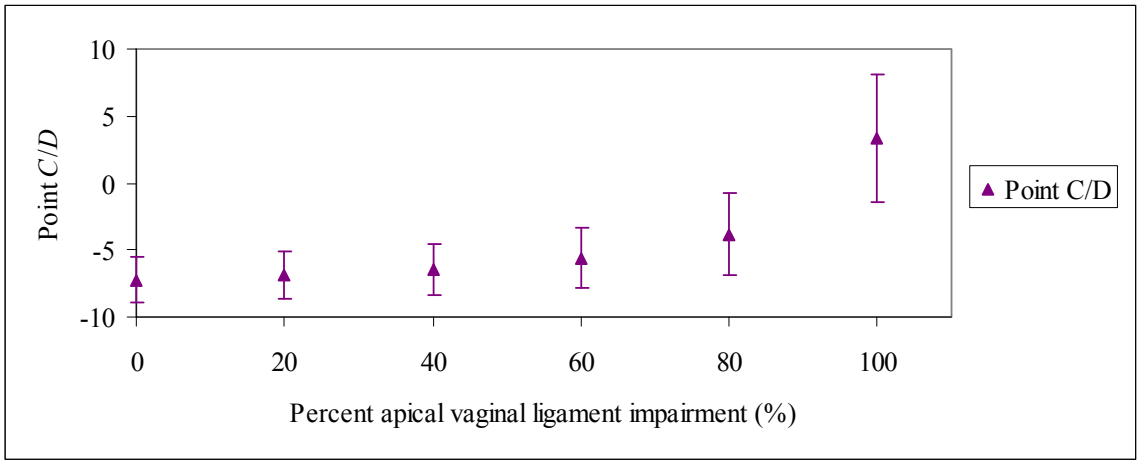

Figure 28 The vaginal apex positions (points *C* or *D*) at 0%, 20%, 40%, 60%, 80% and 100% apical vaginal ligament impairment assessed for patients with primarily apical vaginal ligament impairment (Group 2).

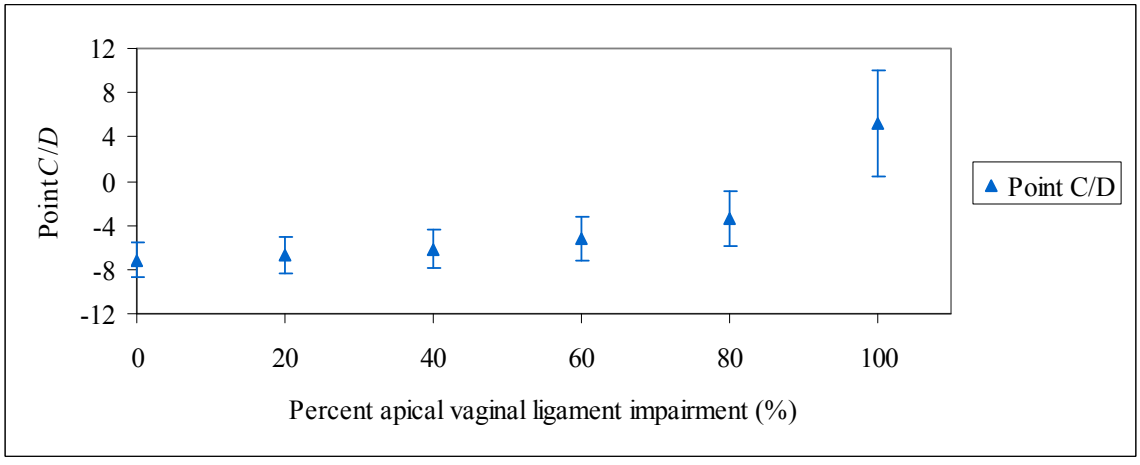

Figure 29 The vaginal apex positions (points *C* or *D*) at 0%, 20%, 40%, 60%, 80% and 100% apical vaginal ligament impairment assessed for patients with apical vaginal ligament impairment and 30% coexisting pelvic floor muscle impairment (Group 3A).

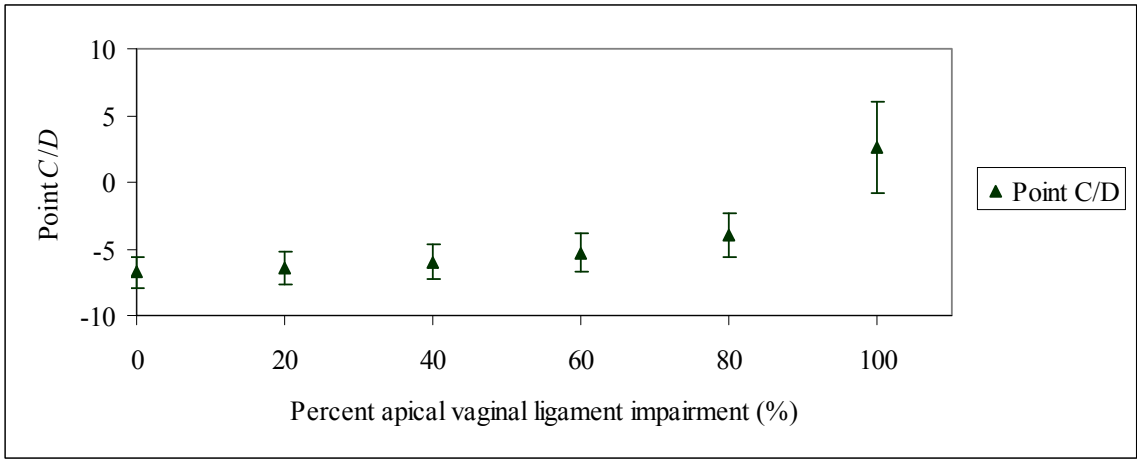

Figure 30 The vaginal apex positions (points *C* or *D*) at 0%, 20%, 40%, 60%, 80% and 100% apical vaginal ligament impairment assessed for patients with apical vaginal ligament impairment and 60% coexisting pelvic floor muscle impairment (Group 3B).

According to Figures 28 to 30, point *C* or *D* prolapse caudally (i.e. become more positive in magnitude) as the percent apical vaginal ligament impairment increases (i.e. from 0 percent to 100 percent ligament impairment). This illustrates that impaired apical vaginal ligaments can directly weaken vaginal apex support. Conversely, points *C* or *D* approach normal positions (i.e. become more negative in magnitude and approach -total vaginal length in *cm*) as the percent ligament impairment decreases to 0 percent. This illustrates that reconditioned apical vaginal ligaments can re-established vaginal apex support for patients with apical vaginal ligament impairment and/or pelvic muscle impairment.

The modeling results outlined in the current section are consistent with clinical condition of pelvic organ prolapse, and they demonstrate the significance of cardinal and uterosacral ligaments to both bladder neck and apical vaginal supports with increases in intra-abdominal pressure. The results are clinically useful, since they not only postulate the degree of vaginal apex rehabilitation that may be required to improve the bladder neck and apical vaginal supports for individual patients, but they also predict the prolapsed conditions that can result when these ligaments are damaged.

Chapter 6

Conclusions and Future Work

The current research examined the contribution of pelvic floor musculature weakness and cardinal and uterosacral ligament weakness to the development of Stress Urinary Incontinence (SUI) by developing and using a biomechanical model of the female pelvic support system. The biomechanical pelvic model was developed based on the knowledge of pelvic anatomy and defects of active and passive support associated with urinary incontinence and pelvic organ prolapse. It was built to simulate the behavior of a pelvic support system during a valsalva maneuver. The current developed model incorporated clinical measures of the Pelvic Muscle Strength test and Pelvic Organ Prolapse Quantification System, and it also used clinical variables from an existing database of female patients with symptomatic pelvic organ prolapse. Using the biomechanical pelvic model and the clinical patient data, the current study performed material parameter estimation for the clinical patients, modeled the general behaviors of pelvic support systems with functional or impaired pelvic muscular and/or apical vaginal ligaments, and assessed the effect of pelvic muscular and/ or ligament defects on the bladder neck and vaginal apical supports for individual patients. Overall, the study aims to examine the role of the pelvic floor muscles and apical vaginal ligaments in the pelvic support system and investigate the effect of compromise of these pelvic supportive structures on the pelvic floor support in relation to urinary incontinence.

In parameter estimation, the parameters that describe the stiffness properties of the vaginal and cardinal and uterosacral ligament tissues were estimated for patients who

exhibited pelvic floor impairments, namely pelvic floor muscle impairment and apical vaginal ligament impairment. The patient-specific parameters were found to vary, illustrating the diverse material properties of pelvic tissues in individual patients. For instance, patients with the same degree of pelvic floor muscle impairment were demonstrated to have varied vaginal and ligament tissue parameters. As well, those with the same degree of pelvic floor muscle and apical vaginal ligament impairment were found to have varied vaginal parameters. Patients who have high magnitude of parameters were suggested to have stiff vaginal and ligament tissues that can increase their stiffness sharply when they are strained. In a pelvic floor support system with pelvic floor defects, the vaginal and ligament tissues are exposed to increase intra-abdominal loading during straining conditions. Vaginal and ligament tissues that can increase their stiffness sharply in response to the increasing strain induced by the increases in intra-abdominal loading may help to minimize the degree of pelvic floor prolapse. On the other hand, patients with low magnitude of tissue parameters were suggested to have more elastic vaginal and ligament tissues that change their stiffness gradually when they are strained. When the pelvic support system with pelvic floor defects is subjected to increases in intra-abdominal loading during a valsalva maneuver, these tissues may not be able to increase their stiffness sharply to resist the straining, and this may lead to severe pelvic floor prolapse. Overall, the material parameters obtained in the current study were demonstrated to be useful for describing the diverse pelvic tissue properties for individual patients with pelvic floor disorders, and they illustrate the tissue properties that may be exhibited in patients with varied degree and types of pelvic floor defects.

In biomechanical pelvic modeling, the current developed model was shown to be capable of simulating the behaviors of the pelvic support systems for healthy subjects and subjects with pelvic muscular and apical vaginal ligament defects during at rest conditions and during a valsalva maneuver. Healthy subjects were simulated to have the same bladder neck and vaginal apex positions during at rest condition and during a valsalva maneuver, while subjects with impaired pelvic floor muscles and/or apical vaginal ligaments were simulated to have prolapsed bladder neck and vaginal apex positions during a valsalva maneuver. The degree of bladder neck and vaginal apex prolapse were demonstrated to be amplified as the degree of pelvic floor muscle

impairment and apical vaginal ligament impairment increase. As well, the severity of bladder neck and vaginal apex prolapse was shown to be most acute when apical vaginal ligament impairment is superimposed onto the pelvic muscle impairment. The simulated pelvic conditions for healthy subjects and patients with pelvic impairments were in reasonable agreement with the literature, and they demonstrated the importance of pelvic muscle strength and apical vaginal ligament integrity to the bladder neck and vaginal apex supports.

In modeling the effect of pelvic muscular and ligament defects on the pelvic support systems in individual patients, the model was programmed with conditions of pelvic floor muscle impairment and/ or apical vaginal ligament impairment, and the resulting bladder neck and vaginal apex positions were assessed. When the model was programmed with increasing degree of pelvic floor muscles and/ or apical vaginal ligaments impairments, both bladder neck and vaginal apex positions were simulated to progress caudally, consistent with the clinical conditions of pelvic organ prolapse; alternatively, when the model was programmed with the conditions of restored pelvic floor muscles and/ or apical vaginal ligaments, the bladder neck and vaginal apex positions were simulated to approach normal positions. The model findings exhibit the impact of compromise of pelvic muscular support and cardinal and uterosacral ligaments on the development of SUI and vaginal apex prolapse with increases in intra-abdominal pressure, and they also suggest a mechanism of how pelvic muscle and vaginal apex rehabilitation impact SUI and vaginal apex supports in patients with coexisting POP symptoms.

On the whole, the current research work has focused on improving our understanding of the relationship between SUI and POP. By means of exploring the relationship between these two pelvic floor disorders, the current research has made several important contributions to the areas of female pelvic floor diseases and biomechanical modeling. Throughout the study, the research team has collaborated with the gynecologists and urologists at the Southern Bladder health Incontinence Centre to integrate the delivery of health care and scientific research. By interacting with the health care professionals and performing literature research, the research team assessed the usefulness of the clinical variables of the current pelvic diagnostic methods in

assessing the severity of SUI and POP symptoms, investigated the inadequacies of the current SUI diagnostic methods and pelvic floor treatment procedures, and proposed solutions of relevance to the clinical needs in improving the diagnostic accuracies and treatment success for patients with both SUI and POP symptoms.

To improve the diagnostic accuracy and treatment success for patients with SUI and POP symptoms, our research team apprehended the importance of identifying and correcting the POP-related pelvic causes that are potentially leading to SUI. Based on literature research, we identified that pelvic floor muscle weakness and apical vaginal ligament weakness are potential POP-related defects leading to the development of SUI symptoms, and we also determined that clinical measures, namely the pelvic muscle strength score and POPQ points (i.e. point *C*/*D*, point *Aa*), of the Pelvic Muscle Strength test and Pelvic Organ Prolapse Quantification System were useful for assessing the weaknesses of pelvic floor muscles, apical vaginal ligaments and bladder neck support.

To explore the mechanism of how these pelvic defects can lead to the symptom of SUI (i.e. weakened bladder neck support), the current study used biomechanical modeling. We extended and modified an existing biomechanical model of a female pelvic system that was previously used to study the interactive role of impaired pelvic floor muscles and apical vaginal ligaments in the development of anterior vaginal wall prolapse. In term of extension, the bladder neck position was incorporated into the model to allow the investigation of the effect of impaired pelvic floor muscles and apical vaginal ligaments on the bladder neck support, an important factor determining the onset of the development of SUI. As well, Pelvic muscle strength score, which assess the pelvic muscle function, and POPQ points (point *C*/*D*, point *Aa*), which assess the apical vaginal support and the bladder neck support, were implemented into the model to allow the quantification of the degree of pelvic floor muscle, apical vaginal ligament and bladder neck support weaknesses. For the first time, standardized clinical measures were incorporated into biomechanical model to facilitate the establishment of the usefulness of clinical tests (Pelvic Muscle Strength test and Pelvic Organ Prolapse Quantification System) for assessing the weakness of pelvic floor muscles and apical vaginal ligaments that are potentially leading the development of SUI. In terms of modifications, the model was modified to allow the investigation of the effect of primarily apical vaginal ligament

impairment, in addition to the effect of primarily pelvic floor muscle impairment and the combined effect of pelvic floor muscle and apical vaginal ligament impairment, on the development of vaginal wall prolapse and SUI. To explore the effect of primarily pelvic floor muscle impairment and the combined effect of pelvic floor muscle and apical vaginal ligament impairment on the development of pelvic floor disorder symptoms, the model was developed based on the presumption that the vaginal prolapse is initiated by reduced pelvic muscle strength. To explore the effect of primarily apical vaginal ligament impairment on the development of pelvic floor disorder symptoms, the model was developed based on the presumption that the vaginal prolapse is initiated by delayed pelvic muscle contraction. By implementing all the extended features and modifications, the model was capable of simulating the behaviors of a pelvic support system during at rest condition and during a valsalva maneuver. To more accurately simulate the pelvic conditions for individual patients with pelvic floor disorders, the current model used clinical variables from an existing database of female patients with symptomatic pelvic organ prolapse. Using the biomechanical model with clinical patient data, the current study estimated the material parameters that describe the pelvic tissue stiffness properties for clinical patients, modeled the general behaviors of both normal pelvic support system and pelvic support systems with pelvic floor muscular and/or apical vaginal ligament defects, and evaluated the effect of varied pelvic muscular and/ or ligament defects on the changes in the bladder neck and apical vaginal support for clinical patients.

In parameter estimation, the material parameters of the pelvic tissues were determined based on the POPQ measures of living female subjects. These parameters describe the vaginal and ligament tissue properties for individual patients, and in research perspective, they are useful for simulating patient-specific pelvic floor behaviors under straining conditions. In pelvic modeling, the simulated behaviors of the normal and abnormal pelvic support systems demonstrated the role of pelvic floor muscles and the apical vaginal ligaments in the pelvic support system. The simulated results illustrated the importance of pelvic muscles and apical vaginal ligaments to the vaginal support, which is crucial to both bladder neck and vaginal apex support. In modeling the effect of pelvic muscular and ligament defect on the pelvic floor support, increased pelvic muscular and apical vaginal ligament defects were demonstrated to contribute to vaginal apex prolapse

and weakened bladder neck support, one of the major symptoms of Stress Urinary Incontinence. On the other hand, reduced pelvic muscular and apical vaginal ligament defects were shown to improve vaginal apex support and bladder neck support. Overall, the current findings exhibit the importance of pelvic muscle strength and intact apical vaginal ligaments on the bladder neck and vaginal apex supports in clinical patients. In terms of SUI management, the findings also highlight the importance of diagnosing and restoring both pelvic floor muscular support and apical vaginal support to better treat the symptoms found in SUI patients with coexisting POP symptoms. To diagnose the pelvic floor muscular defect in individual patients, physicians are encouraged to use Pelvic Muscle Strength test as it is shown in the current study to be a quick and easy test for quantifying the pelvic muscle contraction strength. To rehabilitate the pelvic floor muscles, patients who have pelvic floor muscle impairment are encouraged to perform regular Kegel exercises. To promote bladder neck support and minimize urine leakage in times of strenuous activities, patients are encouraged to learn how to perform a proper Knack maneuver [41, 119]. On the other hand, to diagnose the apical vaginal ligament defect and SUI symptom for individual patients, physicians are encouraged to use the clinical measures of Pelvic Organ Prolapse Quantification System, since it is also shown in the current study an efficient clinical tool for evaluating the vaginal apex support and the bladder neck support. To restore the apical vaginal support, physicians may use vaginal apex fixation procedures. Indeed, the current research intends to enhance the management of SUI patients with POP symptoms by improving the assessment of the pelvic causes of SUI. It is anticipated that more accurate assessment of the pelvic causes of SUI can allow physicians to prescribe more targeted treatments for individual SUI patients with coexisting POP symptoms.

It is important to note that there are some inherent limitations in the current study, and some suggestions for future work are recommended to enhance this type of research. Firstly, the current study had no imaging evidence of damages in the pelvic floor muscles and apical vaginal ligaments that are potentially causing the vaginal prolapse conditions diagnosed in the studied patients; thus, some assumptions relating to the anatomical pelvic causes of the vaginal prolapse conditions for the studied patients were made. For instance, it was assumed that Group 1 patients (i.e. patients with primarily pelvic floor

muscle impairment) exhibited no apical vaginal ligament impairment, and the resulting distal and apical vaginal prolapse demonstrated in these patients were assumed to be primarily due to weakened pelvic floor muscles. On the other hand, Group 2 (i.e. patients with primarily apical vaginal ligament impairment) and 3 (i.e. patients with both pelvic floor muscle impairment and apical vaginal ligament impairment) patients were assumed to exhibit apical vaginal ligament impairment. Patients with coexisting pelvic muscle weakness (Group 3 patients) were assumed to have both impaired pelvic floor muscle and ligament impairment contributing to the resulting distal and apical vaginal prolapse. In the future, it is recommended that we obtained the pelvic images for the individual studied patients with pelvic floor disorders using either Ultrasound or MRI techniques. With imaging evidence of damages in the pelvic floor muscles and apical vaginal ligaments for individual patients with pelvic floor disorders, we can more accurately identify whether the vaginal prolapse demonstrated in individual patients is in consequence of primarily muscle damage or collective damages of muscles and apical vaginal ligaments.

In terms of model inputs, the clinical variables, including the dimensions and inclinations of the pelvic floor structures, the bladder volume and the valsalva pressure, currently used in the pelvic model were all based on literature values. To more accurately simulate the pelvic behaviors of the studied patients with pelvic disorders, it is essential to obtain and use the patient-specific variables measured at the time when they perform a valsalva maneuver. In the future, imaging techniques, such as MRI and ultrasound, can be used to obtain the dimensions and inclination of the pelvic floor structures for individual patients. Urodynamics tests, on the other hand, can be used to measure the bladder volume and the valsalva pressure for individual patients. By gathering and implementing all the patient-specific variables into the model, the simulated pelvic system behaviors for individual patients are anticipated to be more accurate. By comparing the modeled behaviors to the actual behaviors of the pelvic support system during straining conditions, the biomechanical model outputs can also be validated.

In developing the current biomechanical pelvic model, the study had made some simplifying assumptions on some of the pelvic structures. For instance, it was assumed

that the iliococcygeus muscles were hinged on the sacrum and that they would not passively deform, and that the perineal membrane remains stationary during straining condition. As well, in this two-dimensional model, the fascial supports (ie. pubocervical fascia and arcus tendineus pelvic fascia) that provide lateral support to the vagina are not included, since they are complex structures that require 3-dimensional modeling techniques to simulate their behaviors. In the future, the deformation of the iliococcygeus muscles and the perineal membrane, and the fascial supports are needed to be incorporated in the model to allow more realistic simulations of the female pelvic support system. 3-dimensional modeling techniques should be used in the future to allow better assembly of the pelvic anatomy and more accurate predictions relating to the vaginal support conditions with and without the presence of pelvic defects.

Finally, the current research uses biomechanical pelvic modeling to explore the association between vaginal supportive defects and the development of SUI symptoms, mainly weakened bladder neck support. To further enhance our understanding on the association between these site-specific pelvic defects and urinary functions, a model that incorporates urinary structures, including the urethra, bladder and bladder-urethral sphincter, as well as urine flow simulation, is recommended. Such a pelvic model can relate urethral pressure and urine flow to bladder neck support and may be more accurate in assessing the direct impact of pelvic defects on the development of SUI symptoms. Nonetheless, in spite of the limitations of the current research study, our developed biomechanical model captures the quantitative behavior of the pelvic support system under straining conditions, and it proposes an opportunity to assess the mechanisms of how damages in the pelvic floor muscles and apical vaginal ligaments can impact SUI in patients with coexisting POP symptoms.

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