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A 3D FINITE ELEMENT MODEL OF THE FEMALE PELVIC FLOOR FOR THE RECONSTRUCTION OF URINARY INCONTINENCE

A. BHATTARAI[*], R. FROTSCHER[*], M. C. SORA[†] AND M. STAAT[*]

[*] Biomechanics Laboratory, Institute of Bioengineering
Aachen University of Applied Sciences
Campus Jülich, Heinrich-Mußmann-Straße 1, 52428, Jülich, Germany
e-mail: {bhattarai, frotscher, m.staat}@fh-aachen.de,
web page: http://www.fh-aachen.de/forschung/institut-für-bioengineering

[†]Plastination Laboratory, Institute of Anatomy
Medical University of Vienna
Währingerstr. 13, A-1090, Vienna, Austria
e-mail: constantin.sora@meduniwien.ac.at,
web page: http://www.meduniwien.ac.at/sysanat/plast.html

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Abstract. Urinary incontinence is a well known pelvic floor (PF) dysfunction in the aging female. Causes can be mainly assumed to be vaginal delivery and reduced stiffness of supporting structures. These can be addressed effectively through a minimally invasive surgery with an insertion of a Polyvinyl anchoring mesh 'to restore the structure to improve its function': the fundamental principle of the 'Integral Theory System'. Although significant research has been done, an exact cause of incontinence remains elusive, either because of limited knowledge of pelvic floor anatomy or of a lack of anatomically realistic finite element simulations. In order to cope up with such shortcomings and to facilitate an effective treatment method, the detailed study of pelvic anatomy, realistic modeling of pelvic floor functions and 3D finite element simulations of the pelvic floor dynamics during urethral closure and opening are the core interests of this research work.

1 INTRODUCTION

The anatomic structure of human pelvic diaphragm is considered to support pelvic viscera (organs) and to allow the passage of urine and feces. It is also responsible for maintaining the intra-abdominal pressure during the motions associated with daily physical activities. Unlike the male, the female pelvic floor also sustains the pregnancy and facilitates the fetal descent during delivery. From conception to birth, a mother's body undergoes unique physical and mental changes. Current research on old female subjects has dug out some evidences which can be traced from the injuries and severe damages that might occur during delivery.

It is well known that progesterone levels are extraordinarily high during delivery which causes a laxity of ligaments and muscles throughout the female body. This facilitates to widen the way out for fetal descend which normally regains its shape and functions after some time. However, critical damages are still vulnerable for next pregnancy or normal pelvic functions. Among them, pelvic organ prolapse and urinary incontinence (UI) are the most common pelvic dysfunctions among the aging females greatly affecting their quality of life. To the present day, only stress UI is said to be surgically curable which is caused by loss of urethral support due to the damage of supporting structures (fascias, ligaments and muscles).

Following the contention of the *Integral theory* of Petros, the aim of this paper is to establish a finite element model of the female pelvic floor based on patient data and validate it by FE simulations of the normal behavior of the pelvic floor. In this paper, emphasis is given on the detailed description of urethral dynamics and the structures responsible for it.

2 MATERIALS AND METHOD

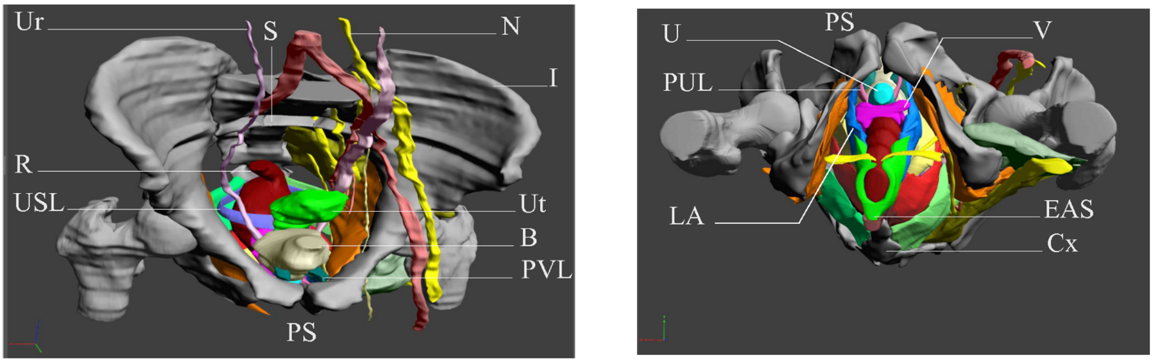
The model was reconstructed from a 70 year old female cadaver specimen obtained from a coroner. The specimen was a part of the human donation program of the Medical University of Vienna. Ethical committee of the university provided approval for using the pelvis for 3D reconstruction: EK Nr: 1191/2011.

2.1 Volume Rendered Computer Model

One female unfixed human cadaver pelvis was used for this study. After removal, the female pelvis was frozen at -80 °C for one week. The frozen tissue block was cut into 1.5 mm thick slices. The slices were dehydrated for 3 weeks in cold acetone. When dehydration was finished, the slices were degreased with methylenchlorid for 10 days. The dehydrated/degreased specimens were submerged in an E12 impregnation mixture [1] in a Heraeus VT 6130 M vacuum chamber and impregnated for 2 days. After impregnation, the slices were removed out of the vacuum chamber and cast between glass plates. The slices were then placed into an oven and hardened for the next 4 days at 45 °C.

In an additional step, we disassembled the glass plates and obtained the finished E12 (epoxy) slices. Each plastinated slice was scanned from both sides using an EPSON GT-10000+ Color Image Scanner at 600 dpi. A ruler (mm) was included in every scan as a calibration marker. Scanned images of the plastinated tissue slices were imported as BMP files into the PC. These images were loaded into WinSURF soft[1] for the reconstruc-

[1]SURFdriver 4.0; http:// www.surfdriver.com



(a) Ventral-superior view **(b)** Lithotomy position, caudal (inferior) view

Figure 1: A computer model of the female pelvic floor including bony pelvis, pelvic viscera, muscles, ligaments and nerves. (Reconstructed from plastinate by Medical University of Vienna).

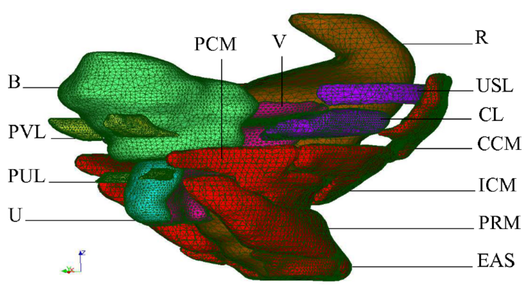
tion step. The objects which had to be reconstructed, were traced manually by using a graphic table (Wacom Cintiq 24HD). Each object was traced and numbered accordingly on every BMP file. After that, the reconstruction was rendered, visualized, and qualitatively checked for surface discontinuities by rotating the model. Reconstructed object were transformed in .OBJ format as shown in Figure 1. Table1 lists the abbreviations used in the figures.

Table 1: Abbreviations used in the figures

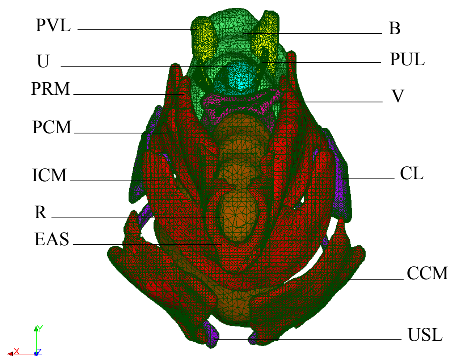
Abbreviation	Full term	Abbreviation	Full term
USL	Uterosacral ligament	CL	Cardinal ligament
PUL	Pubourethral ligament	PVL	Pubovesical ligament
B	Bladder	U	Urethra
V	Vagina	R	Rectum
Ut	Uterus	Ur	Ureter
N	Nerves	LA	Levator ani
PCM	Pubococcygeus muscle	ICM	Illiococcygeus muscle
PRM	Puborectalis muscle	CCM	Coccygeus muscle
EAS	External anal sphincter	Cx	Coccyx
S	Sacrum	PS	Pubic symphysis
I	Ilium		

2.2 Geometrical Model

The next step is the mesh generation from the computer model. The model serves its best for the visualization of the pelvic floor anatomy. Anyhow, due to the complex geometry the reconstructed surfaces show intersecting faces, non-manifod edges and high aspect ratio that makes a FE simulation impossible or at least affect the convergence. Smoothing and repairing the defects is done by using the 3D mesh processing software Meshlab[2] and 3D analysis software Amira[3]. The repaired model is then imported into the open source pre- and post-processor SALOME to create a finite element mesh. Considering the significant thickness of each pelvic constituents, we adopt a volume discretization. A smooth FE mesh as shown in Figure 2 is constructed from linear tetrahedrons (>370,000 elements) except for the vagina that has been discretized with quadratic tetrahedral elements (>22,000) which are required for high precision due to contact between the anterior and posterior walls and between the vagina and adjacent structures (rectum and bladder). The bony pelvis can be considered to be rigid thus it is excluded from the mesh in order to reduce the computation time and cost.



(a) Lateral-ventral view in sitting position



(b) Inferior view in supine position

Figure 2: A 3D finite element mesh of the female pelvic floor based on the data set from the plastinate reconstruction.

Boundary Conditions

Kinematic boundary conditions for the attachment of the pelvic constituents to the bones are specified in terms of appropriate suppression of nodal displacements. The distal end of vagina and urethra are fixed to confirm the zero-displacement in every case of pelvic function. Urethra and bladder are considered to be two different structures sharing common faces hence they are linked together. They are attached to pubourethral and pubovesical ligaments, which in turn are fixed at their other ends assuming the pubis insertion. The lateral walls of the vagina stretch under the action of LA contraction which are represented by directional forces[4] [2]. The upper vagina is suspended at the level of

[2]http://meshlab.sourceforge.net/

[3]http://www.amira.com

[4]Currently, the pelvic muscles are not included in this work, which is replaced simply by applying directional forces in the specific regions of the lateral wall of vagina. Based on the available geometrical representation of the muscle, the muscle model will be included later in the simulation to transmit the forces during contraction and relaxation of LA muscle.

the cervical ring by the cardinal and uterosacral ligaments, the other ends of which are fixed to the pelvic side wall and sacrum, respectively.

3 THE ANATOMY OF PELVIC FLOOR

3.1 Pelvic Ligaments

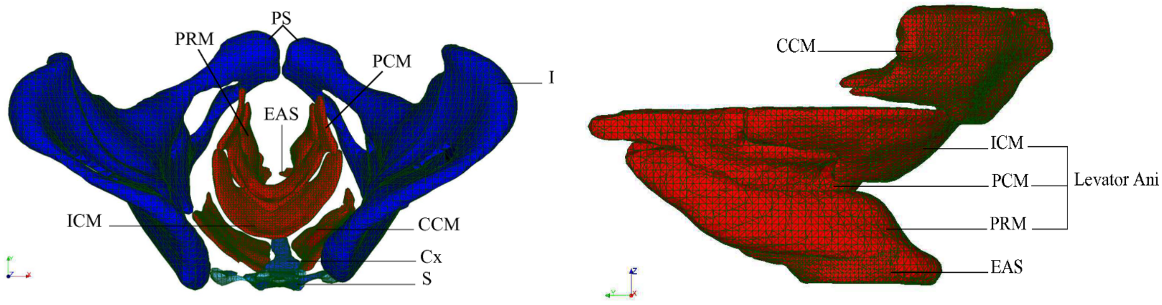
The normal function of the female pelvic organs and maintenance of continence depends on the integrated system of (bony) pelvis, fibromuscular connective tissues, fibro-elastic ligaments and muscular pelvic diaphragm [2], [3]. The pelvis comprises of bony scaffolding connected by a pair of coxal bones with sacrum and coccyx posteriorly and to each other anteriorly at the pubic symphysis. The pubourethral ligament (PUL), a fan like structure, originates from the lower part of each pubic symphysis which bifurcates to insert into the midurehra and lateral vaginal walls [4]. Based on the cadaveric dissection, physical examination in 30 patients presented some evidence of PUL together with muscle in stabilizing urethra in its normal position and maintaining continence [5]. Some research also depicts these ligaments as extensions of the perineal membrane, as well as the caudal and ventral portions of the arcus tendineous fascia pelvis (ATFP) because of their intimate connection. In fact, during sudden increase in intra-abdominal pressure, PUL tightly anchors the anterior wall of the urethra thereby kinking the midurethra.

In [6] and [7] the authors refer to the pubovesical ligament (PVL) and the pubourethral ligament to be synonyms for the same structure that is responsible for the vesical (bladder) neck functioning, urethral support and maintaining continence. Later in [8], histological examination of the vesical neck region has been performed in order to differentiate the existence of both ligaments in terms of orientation and functions: urethral support, continence and initiation of micturition. Therein the existence of the PVL as bands of smooth muscle fibres has been confirmed. It originates from the detrusor muscle at the vesical neck which inserts into the anterior portion of the ATFP and pubic bone. It assist in vesical neck opening and provide rigidity to the bladder [9].

The cardinal and the uterosacral ligaments suspend the apex of the vagina at the level of the cervical ring and support the uterus. The cardinal ligament which is composed of smooth muscle attaches to the lateral pelvic wall to the obturator internus muscle via the obturator fascia. The USL contains a considerable amount of fibrous tissue and non-striped muscular fibers that are attached to the sacrum posteriorly. Weakness and stretching of these ligaments can contribute to uterine prolapse: the drop of the uterus into the vaginal canal.

3.2 Pelvic Diaphragm

Depending on the functional anatomy, skeletal muscles situated at the lower abdomen can be classified into two groups: (1) the obturator internus and the piriformis, which form the pelvic side wall; (2) the coccygeus and levator ani, which together form the pelvic diaphragm [10]. The piriformis and the obturator internus muscles are responsible



(a) Superior view

(b) Lateral view

Figure 3: FE mesh of the striated female pelvic floor diaphragm.

for hip flexion-extension during leg movement and play no role for the continence and structural integrity of the pelvic viscera.

The coccygeus muscle as shown in Figure 3 supports the pelvic viscera. It originates from the ischium spine at the sacrospinous ligament and inserts to the sides of the lower part of the sacrum and the upper part of the coccyx. The Coccygei also supports the coccyx by pulling forward to control defecation. The levator ani is the important muscle of the pelvic diaphragm. The levator ani supports the abdominal pressure and stabilizes pelvic organs by regulating the size of the levator hiatus. It plays a crucial role in the preservation of the urinary and bowel continence. It comprises of three different muscles:

- Pubococcygeus Muscle: It is the fibromuscular layer of pelvic diaphragm which originates approximately 1.5 cm above the inferior pubic symphysis and runs horizontally to insert into the distal vagina [6]. Fibres of PCM from each side sweep behind the rectum to find its attachment at coccyx and sacrum. The strong pubococcygeus muscle contracts to create a forward force which hammock to close the proximal urethra and to control urine flow.

- Illiococcygeus Muscle: At the level of the PCM, illiococcygeal fibres complete the superficial layer of the pelvic diaphragm. It arises from the ischial spine and gets attached anteriolaterally at the junction of the arcus tendineus pelvic fascia and the fascia of the obturator internus muscle. The ICM is supposed to provide major support to the posterior compartment [11].

- Puborectalis Muscle: The PRM is the medial part of the levator ani which closes the pelvic cavity. The fibres of the PRM are oriented almost vertically from the lower part of the pubic symphysis and the superior fascia of the urogenital diaphragm on both sides and loop around the rectum like a sling at the level of the anorectal junction [2]. The inferior fibres of the PRM around the rectum and the fibres of the longitudinal muscle of anus are anchored at the EAS muscle. PRM contracts and pulls the levator plate upwards during sudden increase in abdominal pressure creating a ventral bend between rectum and anal canal to prevent incontinence [12].

3.3 Pelvic Viscera

The female pelvic floor can be divided into three distinct spaces: (1) Urethrovesical space; (2) Vaginal space; and (3) Posterior compartment or rectal space. As shown in

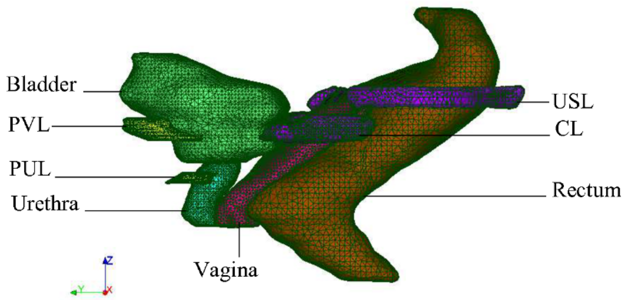


Figure 4: FE mesh of the female pelvic floor without bony pelvis and muscles.

Figure 4, the urethra is directed obliquely downward and forward which connects the urinary bladder to the urethral orifice between clitoris and vagina. The lower two-third of the posterior urethral wall is connected to the anterior vaginal wall via the pubocervical fascia (PCF). The anterior surface is firmly anchored to the symphysis pubis by the pubourethral ligaments and urogenital diaphragm. As the bladder has no inherent shape, a fully distended female bladder rests on the upper part of anterior vagina just below the cervix and creates an additional pressure during sudden increase in intra-abdominal pressure. Weakening or tearing of the PCF may cause cystocele. Behind the vagina the rectum is located which is separated by the rectovaginal fascia.

4 URETHRAL CLOSURE AND OPENING: A COMBINED ACTION OF LIGAMENTS AND MUSCLES

The normal states of the urethra can be defined as: opening during micturition and active closure (closure during effort) [2]. The dynamics of urethral closure and opening mechanisms have been described by Petros as a result of the contraction and relaxation of PCM [2]. Three different perspectives were put forward: urethral, vaginal and mechanical perspective. The main idea was that the relative position of the midurethra due to the development of muscle forces will distinguish the situation of active closure and opening.

During effort, due to a sudden increase in intra-abdominal pressure, LMA and PRM pull the levator ani muscle downward and backward. The displaced LA muscle pulls the vaginal and rectal attachment in the direction of deformation. This will allow the bladder to fall onto the vagina. In the same time, PCM contracts and provides a hammock to the lateral vagina creating a forward force to push the midurethra. With an adequately tight PUL the backward and downward forces are counteracted and the urethra is closed by kinking.

During urethral opening, the PCM relaxes against the PUL. It allows the whole effort system to drop back by LMA and PRM. Due to the conscious contraction of the detrusor muscle, the urethra relaxes to expel out the urine. If either one of the PUL and the PCM is weak by any reasons (e.g. damaged during delivery or reduced stiffness in old age), the position of the urethra can not be stabilized at closure position. This might favors the urine to leak during sudden physical activities or in normal conditions sometimes. This situation is commonly called as urinary incontinence.

5 BIOMECHANICAL STUDY

Almost every soft biological tissues undergoes large deformation. Presence of abundant water requires to consider incompressibility. Therefore, finite strain theories that consider incompressibility and hyperelasticity are used to describe the mechanical behavior. In order to reduce the number of parameters and to simplify the computation for a complex model like the pelvic floor, we utilized a widely used non-linear stress-strain relationship, the Mooney-Rivlin material model that is characterized by the strain energy function

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3), \tag{1}$$

where C_{10} and C_{01} are the material parameters with dimensions of stress at lower and higher level of strains and I_1, I_2 are the principal invariants of the right Cauchy-Green strain tensor. Lacking an alternative, the essential material parameters for each pelvic constituents are adopted from different related literatures. Table 2 lists the material parameters used for the following simulations.

Table 2: Biomechanical properties of pelvic ligaments and pelvic viscera. The mean C_{10} and C_{01} values ($\pm$ SD) in MPa are given below

Type of Structure	C_{10}	C_{01}	Reference
Right uterosacral ligament	1.39 (± 1.4)	12.57 (± 13.57)	[13]
Left uterosacral ligament	1.73 (± 2.12)	8.61 (± 8.08)	[13]
Right broad ligament	1.03 (± 0.9)	8.84 (± 13.02)	[13]
Left broad ligament	0.62 (± 0.45)	4.53 (± 3.44)	[13]
Vagina	0.52	3.25	[14]
Bladder	0.3	0.5	[14]

In the considered simulation, the mechanical properties of the cardinal ligament is defined with regard to the study from [15], which is assumed to be equivalent to that of the broad ligament. In this context the corresponding values for cardinal ligaments were obtained from uniaxial tension tests performed in [13]. Lacking experimental data, the material parameters of USL are used for the PVL and the PUL as well. The comparison of the numerical values prevails ligaments to be stiffer than vaginal tissues. Contrary to that, data from [16] suggests that the ligament stiffness is much lower than that of the vagina. The variation might be due to multiple reasons: age and health of the subject, cadaver storage, ex vivo measurement conditions or experimental setup.

Under physiological conditions, the intra-abdominal pressure (IAP) is imitated by a uniformly distributed load on the upper surface of the vesica. Previous research [17] on a similar pelvic model calculated an average IAP (9.65 kPa) for the subjects at standing positions.

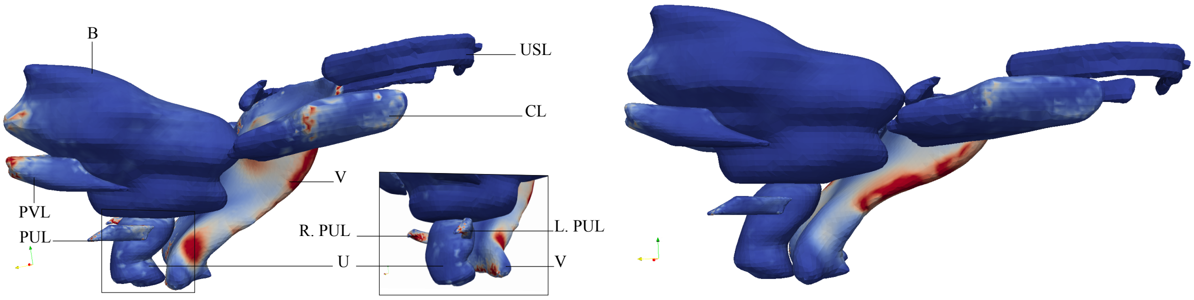
Depending on the functional anatomy as described in sections 2.2 and 3.2, the vaginal surface is acted upon by a set of horizontal and vertical forces to mimic the realistic physiology of the pelvic floor. Petros [2] suggested that bladder neck closure is of primary importance in the maintenance of continence, hence our simulation is mainly centered on the deformed states of urethra, bladder and vagina. For that purpose, a set of horizontal and vertical pelvic muscle forces are directly transferred to the vaginal walls which simplified the model without pelvic diaphragm and rectum, see Figure 4. This not only reduce the large number of degrees of freedom but also lower the computation time because contact is not necessary to be computed between vagina and rectum.

6 RESULTS

The finite deformation simulations for the simplified mesh as shown in Figure 4 are performed in the open source FE software, Code_Aster[5]. The rectum is omitted because it has little influence on the simulated load cases. Loading conditions are applied in accordance to the *integral theory* in order to achieve similar displacement of the structures and to investigate the qualitative behavior of the model. For the material parameters that govern the simulation, we used the values given in Table 2. The simulation is performed in two distinct steps. In the first step, a combined action of the IAP, the LMA and the PRM are applied. Figure 5a shows the bladder and the vagina being displaced backward and downward. The region of interest is magnified and rotated towards the anterior face. It shows that certain stress is developed on the PUL due to the pull from the tight and descended vagina. As the proximal vagina is not directly attached to the urethra, significant tension would have been developed if the vaginal insertion of the PUL was included in the model.

We observe stress concentration at the point of attachment of the ligaments to the organs, especially in the case of the USL and the CL. Those stress concentrations result from the fact that the attachments are modeled using boundary condition. Currently those stress concentrations seem to influence neither the accuracy of the result nor the con-

[5]www.code-aster.org



(a) Vertical descent of pelvic viscera

(b) Contraction of PCM

Figure 5: Finite element simulation of the female pelvic floor showing regions of stress concentration. R. PUL denotes right PUL and L. PUL denotes left PUL.

vergence behavior. Nevertheless, in future simulations those boundary conditions might be replaced in order to improve the model. Contact between the vaginal walls has been successfully simulated though is not visible from the given figure.

In the next step, the PCM contraction is activated by applying a forward pull on the lateral wall of vagina. Forces associated with the first part of the simulation are kept constant. Doing so, the urethra is pushed against the PUL. High stresses are at the lateral wall of the vagina due to the applied PCM force, see Figure 5b. Moreover, the model is under current development and improvements in the additional structures, boundary and contact conditions are still to reduce numerical issues in order to be able to apply larger and more physiological forces.

7 CONCLUSIONS

The focus of this contribution is mainly to investigate the performance of the three dimensional computational model of the female pelvic floor, to model the mechanical processes and to improve the understanding of normal urinary dynamics as suggested by Petros [2]. The model is developed from a realistic anatomic geometry from plastinate reconstruction. All possible pelvic constituents and an appropriate muscular framework close to the data set produced by Janda in [18] are included in the model. Simulation results show the importance of the pubococcygeus muscle in the maintenance of normal urinary continence, moreover, a strong anchorage of the pubourethral ligament is required indeed. The presented model will be further developed in order to simulate functional defects in the pelvic floor and to investigate the quality of respective mesh implants with respect to their ability of recovering incontinence. In related projects we already investigated different meshes and anchoring systems experimentally and computationally [19], [20]. The structure and the material of different meshes varies considerably and therefore the question arises which meshes are preferable to use. One purpose of the model is to develop criteria or quality measures for the meshes via simulations. Moreover the model can be used for the optimization of the mesh implants and their placement because many different load cases and alternatives can be simulated in a short time.

There are several possible improvements that can be made in the preliminary form of this research work. Firstly, approximated directional muscle forces can be replaced by the real muscle model contributing passive stretching and active contraction. Secondly, a simple hyperelastic material model was implemented for the simulation of all PF tissues. More accurate results can be achieved with advanced fibre oriented anisotropic model. And finally, there has been some contradictory findings regarding the relative stiffness of the pelvic constituents. Besides an improved modeling additional experiments need to be conducted in order to derive reliable material parameters.

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