Application of a new method in the study of pelvic floor muscle passive properties in continent women

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Abstract

The aim of this study was to present a new methodology for evaluating the pelvic floor muscle (PFM) passive properties. The properties were assessed in 13 continent women using an intra-vaginal dynamometric speculum and EMG (to ensure the subjects were relaxed) in four different conditions: (1) forces recorded at minimal aperture (initial passive resistance); (2) passive resistance at maximal aperture; (3) forces and passive elastic stiffness (PES) evaluated during five lengthening and shortening cycles; and (4) percentage loss of resistance after 1 min of sustained stretch. The PFMs and surrounding tissues were stretched, at constant speed, by increasing the vaginal antero-posterior diameter; different apertures were considered. Hysteresis was also calculated. The procedure was deemed acceptable by all participants. The median passive forces recorded ranged from 0.54 N (interquartile range 1.52) for minimal aperture to 8.45 N (interquartile range 7.10) for maximal aperture while the corresponding median PES values were 0.17 N/mm (interquartile range 0.28) and 0.67 N/mm (interquartile range 0.60). Median hysteresis was 17.24 N∗mm (interquartile range 35.60) and the median percentage of force losses was 11.17% (interquartile range 13.33). This original approach to evaluating the PFM passive properties is very promising for providing better insight into the patho-physiology of stress urinary incontinence and pinpointing conservative treatment mechanisms.

Keywords

- Levator ani;
- Resting forces;
- Stiffness;
- Tone;
- Dynamometry;
- Continence

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1. Introduction

The pelvic floor muscles (PFMs) play a crucial role in maintaining continence since they participate in urethral occlusion (DeLancey, 1988). It has been shown that an involuntary PFM contraction occurs in asymptomatic women during rises in intra-abdominal pressure (i.e. coughing) in order to constrict the urethra and thus prevent urine leakage (Constantinou and Govan, 1981, Bo et al., 1994, Peschers et al., 2001 and Shafik et al., 2002). In addition to this sphincteric function, the PFMs are reported to act, with other structures (fascias, ligaments, connective tissues), as a passive supportive hammock against which the urethra is compressed during increases in intra-abdominal pressure (DeLancey and Ashton-Miller, 2004 and Ashton-Miller and DeLancey, 2007). From these theories, it can be hypothesized that continent women have higher passive stiffness in their pelvic floor musculature than women with stress urinary incontinence, which would provide a firmer backstop under the urethra during coughing and, hence, an effective urethral occlusion. This supportive function of the PFMS at rest remains understudied and poorly understood.

In an effort to standardize PFM function assessment, a sub-committee of the International Continence Society claims the need to develop a method to objectively quantify the passive properties of the PFMs, also called PFM tone (Messelink et al., 2005). To date, PFM passive properties are estimated by introducing a finger, a pressure probe or a dynamometric speculum into the vaginal cavity. For digital examination,Devreese et al. (2004) reported the use of a 3-point scale (normo-, hypo-, hypertone) in continent and incontinent women. However, despite its usefulness in a clinical setting, this assessment technique remains subjective. Regarding the passive PFM forces evaluated with a vaginal pressure probe (Griffin et al., 1994), these measurements are taken at a fixed vaginal aperture depending on the diameter of the probe. The resting pressure recording may therefore be biased by the size of the urogenital hiatus; in other words, for women with a larger hiatus, the hiatus may exceed the probe circumference and the resting pressure cannot be properly recorded since the vaginal walls are not fully in contact with the probe. In our previous work (Morin et al., 2004) as well as in the study of Verelst and Leivseth (2007), the assessment of PFM passive forces was done at selected and adjustable vaginal apertures but the presence of PFM involuntary contractions, which can contaminate the passive forces recorded (Gajdosik, 2006), was not monitored. Moreover, these measurements were made during static stretches (i.e. the vaginal aperture was increased and recordings were made after a rest period when the forces were stable). Considering that the passive properties of muscles are dependent on time (Magnusson, 1998), dynamic stretching may provide useful information on continence mechanisms by assessing the viscoelastic properties of the PFMs.
The aim of this study was to describe a novel methodology for evaluating the passive properties of PFM, to determine the optimal number of lengthening and shortening cycles over which to average data values, and to investigate the interrelationships among various passive viscoelastic properties in order to determine which measures are redundant. Data are reported for asymptomatic women but the method is also

applicable for women suffering from stress incontinence. This approach combining force and electromyographic (EMG) measurements is based on methodology and concepts already used for the estimation of passive properties of structures surrounding peripheral joints such as the ankle (Magnusson, 1998 and Gajdosik, 2001). The technique used to assess such passive properties consists in mechanically moving the joint within the tolerable range of motion as forces are recorded. The joint is displaced slowly to avoid stretch reflexes and the absence of EMG activity is monitored to be sure that only the passive component of muscle force is involved in the measurement. A secondary aim of this study was to verify the participants' acceptance of the new PFM procedure.

2. Methods

2.1. Subjects

Thirteen continent women participated in the study. They were all physical therapists specialized in PFM dysfunction. The reason why this population was targeted is that this study was part of another research project which required the participants to have a fair knowledge of the PFM anatomy and physiology. From a membership list provided by the professional association of physical therapists (Ordre professionnel de la physiothérapie du Québec), informational pamphlets were sent to all potential participants in the Montreal area (Canada). The women included in the study had to be 45 years old or less with no urogynecologic symptoms. Exclusion criteria were pregnancy, urinary and anal incontinence, urinary urgency, anterior urogynecologic surgery, organ prolapse (POP-Q > 1 (Bump et al., 1996)), current urinary or vaginal infection, excessive vaginal scarring, vulvar or vaginal pain or any other disease that may interfere with PFM measurements. Moreover, to prevent any discomfort, the women participating in our study were not evaluated during their menstrual period. All women gave written consent to participate in the study, which was approved by the Ethics Committee of the Centre for Interdisciplinary Research in Rehabilitation. In addition to the interview for verifying the exclusion criteria, the absence of incontinence and other urogynecologic symptoms was confirmed with the Urogenital Distress Inventory questionnaire (Shumaker et al., 1994) and a modified 20-min pad test with a standardized bladder volume (⩾250 mL) (Abrams et al., 1988 and Sand, 1992). The latter was measured by ultrasound with the Bladder Scan 3000 (Diagnostic Ultrasound). One hour before the test, the subjects were asked to drink 1 L of water and the test was performed when the bladder contained more than 250 mL. In interpreting the results, subjects with a pad weight less than 1 g were considered continent (Abrams et al., 1988).

2.2. Instrumentation

Assessment of the PFM passive properties was done using a modified version of the dynamometric speculum used in our previous research (Dumoulin et al., 2003). The modified dynamometric speculum comprises two aluminum branches (lower and upper) measuring 19.4 mm in width (Fig. 1). Compared to the initial version, the size of the speculum has slightly changed. The lower branch now comprises two blades: blade 1 is designed to be located deep in the vagina (6 cm) in order to monitor intra-abdominal pressure during coughing; it has already been used in another study (Morin et al., 2006). Blade 2, located at the level of the PFMs, proved to be valid for PFM assessment (Morin et al., 2006). Both blades are equipped with Wheatstone bridges using differential arrangements, which ensures that the force is measured independently of the exact site of application of the resultant force (Avril, 1984, Bourbonnais et al., 1993 and Dumoulin et al., 2003). The initial and modified versions of the dynamometric speculum have both shown good reliability with repeated measurements (Dumoulin et al., 2003, Dumoulin et al., 2004 and Morin et al., 2007). Most importantly, the modifications to the initial version included a higher performance linear actuator, which was essential for the assessment of the PFM passive properties. The upper branch is now fixed while a precise and smooth linear motion system (MicroStage MS33-LDB-L200, Thomson Industries Inc.) allows a 5-mm downward displacement of the lower branch (both blades) for one revolution of the crank. A linear position transducer (Honeywell MLT-38000-101) connected to the lower branch has been added to allow real-time monitoring of the vaginal antero-posterior diameter. The dynamometric speculum is positioned on a stable base and the angulations of the speculum can be adjusted to the natural vaginal orientation.

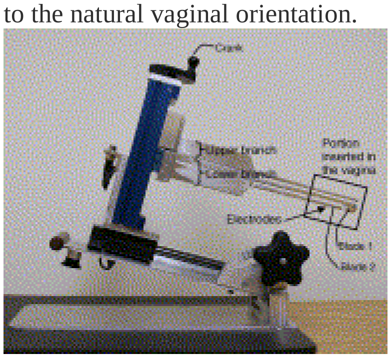

Fig. 1.

The lower branch comprises two blades. The passive properties were recorded with blade 2, which is located at the level of the PFMs. In the picture, the speculum is opened to the minimal aperture, which corresponds to a vaginal antero-posterior diameter of 15 mm (distance between lower and upper branches). As also shown, the speculum can be tilted to respect woman's natural vaginal orientation; the portion of the speculum inserted into the vagina corresponds to 6 cm.

Pelvic floor EMG signals were used to determine whether an active or passive component was involved. Prior to insertion of the speculum into the vaginal cavity, each branch was covered with a condom and disposable surface electrodes were stuck on the condom covering blade 2 of the lower branch. In order to ensure that PFM activity was properly recorded, four pairs of Medtronic electrodes (#9013L4611, each 6 mm in diameter), with distances of 3 mm between the electrodes and 4 mm between each pair, covered the entire area of blade 2. A bipolar configuration was used to maximize the selectivity of the EMG recordings. The ground electrode (Kendall, Meditrace) was positioned over the great trochanter area. The EMG signals were amplified (gain 1000) and bandpass-filtered (10–500 Hz) before being rectified and averaged for successive time periods of 125 ms.

The EMG and the signals of the dynamometric speculum (force and position) were transferred to a portable computer (Toshiba Satellite, Pentium 4) equipped with a 12-bit acquisition card (NIDAQCard-6024E, National Instrument Corporation). The acquisition of these inputs was synchronized; the sampling rate was 1024 Hz. The voltage from the strain gauges was converted to force values in Newton (N) using an *in vitro* calibration (i.e. calibrated loads were applied to the lower branch to measure the output voltage and, thus, to determine the converting factor). Since the modified dynamometric speculum is based on the same technology as the initial version (Dumoulin et al., 2003), the *in vitro*calibration properties (linearity, repeatability, hysteresis and independence of the site of application) were as excellent.

2.3. Passive-property measurements

The PFM assessment was conducted entirely by an experienced physiotherapist properly trained in dynamometric and EMG measurements. It should be noted that the women were asked to empty their bladder before the dynamometric assessment. Women adopted a supine position with hips and knees flexed, feet flat on a conventional gynecologist's table. The ability of the subjects to correctly contract and relax their PFMs was confirmed by vaginal digital palpation. The speculum, set at minimal aperture and lubricated with a water-soluble jelly, was inserted in the vagina to a depth of 6 cm. Considering the design of the speculum, the minimal vaginal opening (when the two branches were closed) corresponds to an antero-posterior diameter of 15 mm. To ensure that they were comfortable and to familiarize them with the device inserted, the women were asked to perform three unrecorded practice PFM contractions.

In order to measure the passive component specifically, the participants were instructed to relax their PFMs as much as they could using EMG signals as biofeedback. During the PFM passive-property assessment, the evaluator had access to the EMG and force signals on the computer screen in order to ascertain that the subject performed the task correctly. The data were then stored on hard disk. A trial was rejected if the absolute mean EMG reached twice the resting values in at least one pair of electrodes. The program displayed such increases in red on the screen monitored by the evaluator. EMG monitoring was used to ensure that each force curve remained unaffected by active contraction of muscles. Moreover, the smoothness in the increase and decrease in force with changes in aperture was checked in order to eliminate trial contamination by artefacts originating from body instability or other causes not related to passive properties.

The PFM passive properties were evaluated in four different conditions. A rest period of 2 min with the speculum closed at minimal aperture was respected between each condition.

2.3.1. Initial passive resistance

The PFM passive forces were registered at minimal vaginal aperture (15 mm), i.e. the minimal distance made physically possible by the design of the speculum. The mean force was calculated over a 5-s period.

2.3.2. Passive resistance at maximal aperture

The maximal stretching amplitude was determined by either the patient's tolerance limit or the increase in EMG activity (Gajdosik, 2001). As for condition 1, the forces were averaged over 5 s.

2.3.3. Passive properties during lengthening and shortening cycles

The PFMs and surrounding tissues were stretched by separating the two speculum branches at a constant speed (5 mm/s). When the maximum vaginal aperture was reached, the branches were closed at constant speed to minimal aperture. To do so, the evaluator had to follow a template on the screen based on the maximal aperture found in condition 2. As a familiarization trial, five stretch–relax cycles at 80% of the maximal aperture were carried out. Subsequently, five stretch–relax cycles at 100% of the maximal aperture were performed. Various parameters were extracted from the force–aperture, as illustrated in Fig. 2. The force–aperture curve was computed for each cycle by plotting the force values for fixed increments of aperture (ΔL = 0.1 mm) using the minimal aperture as a starting reference. Different force, aperture and passive elastic stiffness (PES: slope of force–aperture curve) parameters were extracted from the lengthening phase of the passive force–aperture. For averaging purposes, we selected the maximal and minimal apertures that were common for the last four cycles (apertures reached for all four of the last cycles). The force parameters were: (a) force at minimal aperture (F_{MIN}); (b) force at maximal aperture (F_{MAX}); (c) force at mean aperture (F_{MEAN}), i.e. the force at the aperture between the minimal and maximal apertures; and (d) force at a common aperture of 25 mm (F_{25}). This is the highest aperture recorded in all subjects and is useful in the between-subject comparison: a subject's PFMs with a higher value of force at this aperture than another subject's were considered stiffer. The aperture at a common force of 3.5 N ($A_{3.5}$) was also calculated and can be interpreted as follows: when a subject presents a lower aperture than another subject for this common force of 3.5 N, her PFMs were considered stiffer. The PES parameters were calculated using the average values of ten PES data point increments (10 * 0.1 mm = 1 mm) in order to smooth the derivative characteristic (i.e. to avoid high slope variations due to experimental signal artefacts). The PES values were found at minimal aperture (PES_{MIN}); maximal aperture (PES_{MAX}); mean aperture (PES_{MEAN}) and at the common aperture of 25 mm (PES_{25}). The last parameter computed from the force–aperture curve was the hysteresis, i.e. the area between the lengthening and shortening curve, which represents the loss of energy associated with tissue lengthening.

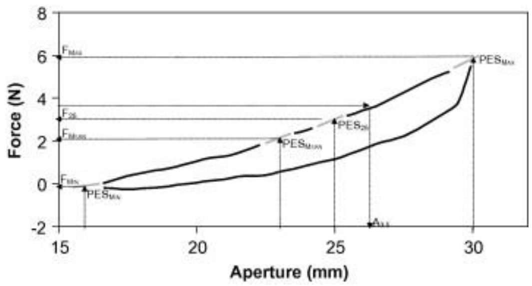

Fig. 2.

The means of cycles 3, 4 and 5 are presented. The PES parameters are given by the slope of the curve at the selected points. Passive parameters extracted from the force–aperture curve are illustrated: force (F_{Min}) and passive elastic stiffness (PES_{Min}) at minimal aperture, force (F_{Max}) and passive elastic stiffness (PES_{Max}) at maximal aperture, force (F_{Mean}) and passive elastic stiffness (PES_{Mean}) at mean aperture, force (F_{25}) and passive elastic stiffness (PES_{25}) at the common aperture of 25 mm, aperture at a common force of 3.5 N ($A_{3.5}$) and hysteresis (area between the lengthening and shortening curves).

The parameters were calculated for all five cycles. On visual inspection of the force/aperture curves, a progressive superposition of the last three curves was noted (see Fig. 3 specifically) suggesting that averaging the last three cycles may provide more stable and representative passive parameters of the PFMs. Moreover, the evaluator reported difficulty in following the template during the first cycle. This difficulty was explained by the small delay allowed for initiating the data collection (by pressing the start button) then taking the dynamometer to increase the vaginal aperture. This feature was corrected after the study. For a more rigorous selection of the cycles in the present study, we performed an intra-class correlation analysis (generally used for a reliability study) on successive series of three cycles (1, 2, 3; 2, 3, 4; 3, 4, 5).

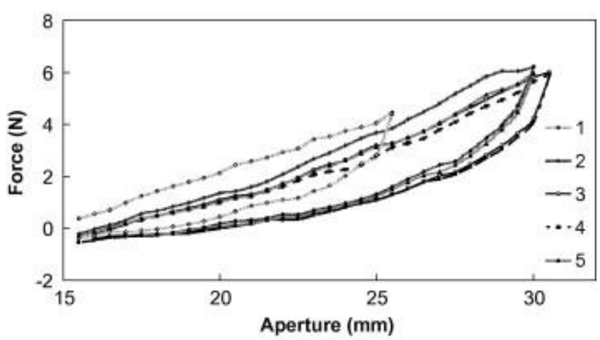

Fig. 3.

This figure represents five PFM lengthening and shortening cycles, performed at constant speed in one subject. It may be noted that a progressive superposition of the curves appears in the last three cycles (3, 4, and 5). As observed, the force during the shortening phase is lower than the force during the lengthening phase for the same aperture.

2.3.4. Sustained stretch

The speculum was again opened at maximum aperture and the stretch was sustained for 1 min. In the language of applied mechanics, this behavior is known as the stress–relaxation of the structure. The percentage of passive resistance loss after 1 min of sustained stretch at maximal aperture was calculated as:

$$\left(\frac{\text{Maximal PFM forces detected during the initial stretching phase} - \text{mean PFM forces after 1 min}}{\text{Maximal PFM forces}} \times 100\right)$$

The participants were also asked to execute a PFM maximal voluntary contraction while breathing out for 10 s. The maximal strength was calculated by subtracting the baseline resting forces from the highest maximal force recorded. Furthermore, after the testing the participants were asked to score on a visual analog scale, the acceptability of the procedure. (A score of 10 means that the procedure is highly acceptable, without any discomfort, while the opposite, 0, denotes that the procedure is painful and not acceptable.)

2.4. Statistical analysis

The quantitative data analysis was performed using Matlab TM (version 7.0.1). Descriptive statistics (mean and standard deviation (SD)) were computed for all the passive parameters. We also reported median scores since some parameters were not normally distributed. In condition 3 (lengthening and shortening cycles), the systematic difference across cycles was assessed using a type II intra-class coefficient (Shrout and Fleiss, 1979) and standard error of measurement (SEM) (Shavelson, 1991). The purpose of these analyses was to assess which cycles should be averaged in order to have more stable and representative passive parameters of the PFMs. Spearman correlation coefficients were calculated to investigate the relation between passive parameters in order to assess which parameters may be redundant in the muscle evaluation. Using reliability analyses (Morin et al., 2008) and a study comparing continent and stress urinary incontinent women, it may, in future, be possible to reduce the number of parameters. The significance level was set at 0.05.

3. Results

The subjects had a mean (±1 SD) age of 32 (±8) years and body mass index of 21.1 kg/m^2 (±1.1 SD). They had a mean parity of 1 (±2 SD), 10 being nulliparous and 3 multiparous. The mean bladder volume measured before the pad test was 427 mL (SD 157; range 250–745 mL). All the subjects were considered continent in the pad test with a pad weight gain after the test less than 1 g (mean 0.2 g; SD 0.2 g; range 0.0–0.4 g), which may be attributed to weighing errors, sweating or vaginal discharge (Abrams et al., 1988).

As stated earlier, the evaluator had access to the force and EMG curves to verify the acceptance of the data. Among all the trials, only two had to be redone because of an increase in EMG activity with increasing the aperture, and these two trials were in different subjects. For example, Fig. 4 illustrates a PFM involuntary contraction at the end of a sustained stretch condition.

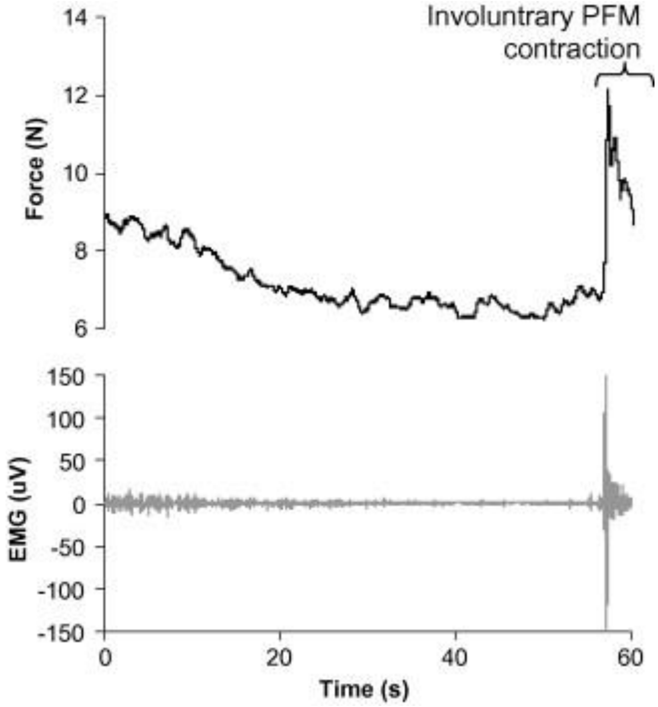

Fig. 4.

During the sustained stretch condition, the vaginal aperture is increased to maximal aperture and the stretch is maintained over 60 s. A progressive reduction of the pelvic floor resting forces can be observed with minimal resting EMG activity. However, at the end of the condition, an involuntary PFM contraction can be observed on either the force or the EMG curve.

The intra-class correlation coefficients generally demonstrated that the stability of the parameters across cycles was higher for the series 3–4–5 than for the others (Table 1). Therefore, the results for the lengthening and shortening conditions are presented as the average of the 3rd, 4th and 5th cycles.

Table 1.

Relevance of cycles in the lengthening and shortening condition using intra-class coefficients, absolute standard error of measurement (SEM_{ABS}) and standard error of measurement as percentage of mean value ($SEM_{\%}$).

Lengthening and shortening condition	Intra-class coefficients for cycles 1–2–3	Intra-class coefficients for cycles 2–3–4	Intra-class coefficients for cycles 3–4–5
F_{Min}	0.92 SEM_{ABS} = 0.36 $SEM_{\%}$ = 69.1%	0.97 SEM_{ABS} = 0.19 $SEM_{\%=}$50.9%	0.97 SEM_{ABS} = 0.19 $SEM_{\%}$ = 47.6%
F_{Max}	0.83	0.83	0.98

Lengthening and shortening condition	Intra-class coefficients for cycles 1–2–3	Intra-class coefficients for cycles 2–3–4	Intra-class coefficients for cycles 3–4–5
	SEM_{ABS} = 1.96 $SEM_{\%}$ = 23.7%	SEM_{ABS} = 1.96 $SEM_{\%}$ = 23.3%	SEM_{ABS} = 0.58 $SEM_{\%}$ = 7.1%
F_{Mean}	0.88 SEM_{ABS} = 0.78 $SEM_{\%}$ = 19.2%	0.97 SEM_{ABS} = 0.36 $SEM_{\%}$ = 9.2%	0.99 SEM_{ABS} = 0.23 $SEM_{\%}$ = 6.0%
F_{25}	Data not available for all subjects	0.96 SEM_{ABS} = 0.55 $SEM_{\%}$ = 11.6%	0.99 SEM_{ABS} = 0.32 $SEM_{\%}$ = 7.0%
PES_{Min}	0.58 SEM_{ABS} = 0.21 $SEM_{\%}$ = 81.6%	0.71 SEM_{ABS} = 0.12 $SEM_{\%}$ = 66.0%	0.71 SEM_{ABS} = 0.12 $SEM_{\%}$ = 65.7%
PES_{Max}	0.96 SEM_{ABS} = 0.55 $SEM_{\%}$ = 87.4%	0.71 SEM_{ABS} = 0.19 $SEM_{\%}$ = 28.5%	0.71 SEM_{ABS} = 0.18 $SEM_{\%}$ = 27.6%
PES_{Mean}	0.95 SEM_{ABS} = 0.45 $SEM_{\%}$ = 43.7%	0.99 SEM_{ABS} = 0.23 $SEM_{\%}$ = 21.8%	0.99 SEM_{ABS} = 0.17 $SEM_{\%}$ = 16.5%
PES_{25}	Data not available for all subjects	0.98 SEM_{ABS} = 0.33 $SEM_{\%}$ = 32.7%	0.98 SEM_{ABS} = 0.28 $SEM_{\%}$ = 28.3%
$A_{3.5}$	Data not available for all subjects	0.99 SEM_{ABS} = 0.48 $SEM_{\%}$ = 2.0%	0.99 SEM_{ABS} = 0.48 $SEM_{\%}$ = 1.9%
Hysteresis	0.93 SEM_{ABS} = 7.32 $SEM_{\%}$ = 22.1%	0.96 SEM_{ABS} = 4.59 $SEM_{\%}$ = 14.6%	0.97 SEM_{ABS} = 3.91 $SEM_{\%}$ = 13.3%

The PFM passive properties assessed in 13 continent women are shown in Table 2. The stress–relaxation parameter indicates a mean reduction of 14.75% (SD 12.15%) in the forces after 1 min of sustained stretching. The mean force–aperture curve shows the PFM forces increasing as the vaginal opening increases to its maximal aperture (Fig. 5). The force–aperture relation was linear in the range of apertures assessed. Coefficients of determination were computed for each subject considering the mean curve of the cycle 3–4–5. A mean coefficient of determination of 0.98 (SD 0.01; range 0.96–0.99; $p < 0.001$) was obtained. Moreover, we also observed the hysteresis phenomenon (area between the stretching and lengthening curve), which is the difference between the energy absorbed during the stretching phase and the energy released during the return phase. The mean PFM active strength was 10.0 N (SD 7.0).

Table 2.

PFM passive properties in four conditions.

Conditions	Parameters	Mean (SD)	Median (interquartile range)
1. Initial passive resistance at minimal aperture	Passive forces (N)	1.03 (1.12)	0.80 (3.10)
2. Passive resistance at maximal aperture	Passive forces (N)	6.18 (2.84)	6.08 (5.05)
	Maximal vaginal aperture (mm)	33.52 (7.26)	30.95 (6.39)
3. Lengthening and shortening cycles (mean of cycles 3–4–5)	F_{Min} (N)	0.35 (1.09)	0.54 (1.52)
	F_{Max} (N)	8.15 (3.97)	8.45 (7.10)
	F_{Mean} (N)	3.82 (2.05)	4.16 (2.83)
	F_{25} (N)	4.54 (2.75)	4.29 (4.44)
	PES_{Min} (N/mm)	0.17 (0.20)	0.17 (0.28)
	PES_{Max} (N/mm)	0.68 (0.32)	0.67 (0.60)
	PES_{Mean} (N/mm)	0.49 (0.25)	0.45 (0.34)
	PES_{25} (N/mm)	0.36 (0.34)	0.39 (0.29)
	$A_{3.5}$ (mm)	24.70 (5.75)	23.44 (7.37)
	Hysteresis (N*mm)	27.09 (21.20)	17.24 (35.60)
4. Sustained stretch	Percentage of passive force losses after 1 min (%)	14.75 (12.15)	11.17 (13.33)

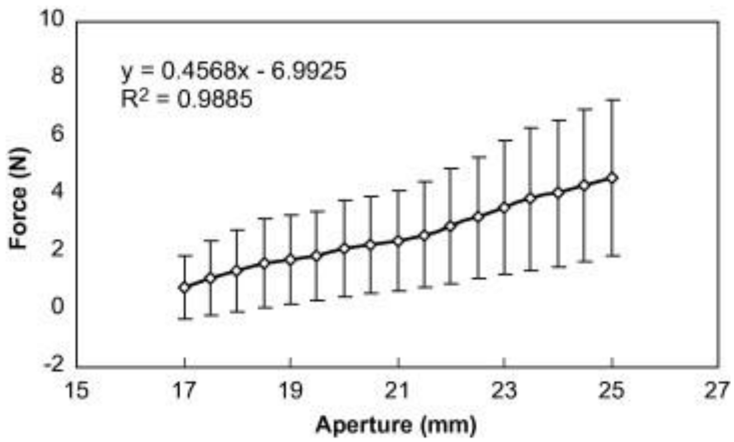

Fig. 5.

The mean force–aperture in 13 asymptomatic women. The aperture illustrated ranged from minimal vaginal opening to a common aperture of 25 mm for all subjects. Brackets represent 1 SD.

Correlations among the passive parameters are shown in Table 3. A Strong correlation (0.89) is seen between the initial passive resistance and F_{MIN} and between the passive resistance at maximal aperture and F_{MAX} (0.97). Generally, the PES parameters are linked more to their corresponding force parameters (PES_{MAX} vs F_{MAX}, PES_{MEAN} vs F_{MEAN}, etc.). The aperture variable ($A_{3.5\,N}$) is negatively correlated to the other variables. Finally, the hysteresis is associated with the parameters at maximal aperture.

Table 3.

Spearman correlation coefficients between PFM passive parameters. *P* values are in parentheses. Significant correlations are highlighted.

	Passive resistance at maximal aperture	F_{min}	F_{max}	F_{mean}	F_{25}	PES_{min}	PES_{max}	PES_{mean}	PES_{25}	$A_{3.5\,N}$	Hysteresis
Initial passive resistance	0.32 (0.28)	0.89 (<.01)	0.28 (0.42)	0.60 (0.03)	0.91 (<.01)	0.42 (0.15)	0.10 (0.73)	0.55 (0.05)	0.03 (0.93)	−0.89 (<.01)	−0.32 (0.28)
Passive resistance at maximal aperture		0.31 (0.30)	0.97 (<.01)	0.87 (<.01)	0.33 (0.26)	0.42 (0.16)	0.65 (0.02)	0.77 (<.01)	0.14 (0.64)	−0.35 (0.24)	0.60 (0.03)
F_{min}			0.31 (0.31)	0.64 (0.02)	0.85 (<.01)	0.21 (0.49)	0.06 (0.84)	0.54 (0.06)	0.01 (0.99)	−0.82 (<.01)	−0.33 (0.27)
F_{max}				0.85 (<.01)	0.29 (0.33)	0.35 (0.19)	0.59 (0.04)	0.71 (0.01)	0.12 (0.69)	−0.30 (0.32)	0.63 (0.02)
F_{mean}					0.61 (0.03)	0.32 (0.28)	0.51 (0.08)	0.86 (<.01)	−0.05 (0.87)	−0.62 (0.02)	0.38 (0.20)
F_{25}						0.53 (0.06)	0.21 (0.48)	0.68 (0.01)	0.16 (0.60)	−0.99 (<.01)	−0.42 (0.16)
PES_{min}							0.21 (0.49)	0.42 (0.16)	0.65 (0.02)	−0.58 (0.04)	−0.04 (0.89)
PES_{max}								0.78 (0.01)	0.18 (0.55)	−0.20 (0.52)	0.28 (0.35)
PES_{mean}									0.16 (0.60)	−0.69 (0.01)	0.14 (0.65)
PES_{25}										−0.20 (0.52)	−0.28 (0.35)
$A_{3.5\,N}$											0.40 (0.17)
Hysteresis											

All the subjects stated that the procedure is pain-free and scored a mean of 8.7 (±1.1 SD, range 7–10) on the visual analog scale, indicating that the methodology is highly acceptable. Their only comments were about the duration of the assessment, since this protocol was followed by a protocol for another study (Morin et al., 2006).

4. Discussion

An original method for assessing the PFM passive properties was applied in continent women. This technique was developed to better understand the involvement of the pelvic floor musculature in its supportive and passive function for the maintenance of continence.

When a resting muscle is stretched passively, several structures and mechanisms contribute to the passive properties. First, Campbell and Lakie (1998) suggested the presence of an actin and myosin cross-bridge formation. Low-level activity associated with actin and myosin cross-bridges in a relaxed skeletal muscle is reported to be non-detectable using surface EMG. The passive state in a muscle is therefore defined by the minimal and negligible EMG activity (Gajdosik, 2001). In our study, the presence of PFM activity below the detectable threshold cannot be fully excluded. We selected a threshold of twice the mean resting value but in fact resting EMG below that threshold is possible.Deindl et al. (1994) have suggested the presence of resting EMG in the PFMs or a "tonic pattern" in PFMs using needle EMG. However, they found that this pattern was not consistent in all women (Deindl et al., 1994). Takezawa et al. (1998) also showed that the extensibility of actin and myosin monofilaments alone contributes to muscle stiffness. Second, Gajdosik (2001) reported that passive-property measurements are influenced by titin, an endosarcomeric cytoskeleton protein, and desmin, an exosarcomeric cytoskeleton protein. Because actin–myosin cross-bridges and cytoskeleton proteins reside within the muscle tissue, increases in muscle mass or muscle hypertrophy following strength training have been linked to higher passive resistance and PES in hamstring muscles (Klinge et al., 1997). The extent to which these structures affect PFM passive properties remains unknown. However, PFM strength training for stress urinary incontinence has shown high effectiveness (Hay-Smith and Dumoulin, 2006) and has been recognized as a first-line treatment (Wilson et al., 2005). Recently, using MRI,Dumoulin et al. (2007) observed a reduction of the genital hiatus at rest, which is the area encircled by the levator ani, suggestive of PFM passive tone or hypertrophy following physiotherapy. Direct passive-property assessment is therefore needed to better understand the role of passive properties in treatment mechanisms of action. Lastly, connective tissues of the endomysium, perimysium and epimysium, with their collagen content, contribute to passive resistance to stretching (Borg and Caulfield, 1980). Women with stress urinary incontinence showed an altered collagen profile in the skin, the uterosacral, and the round ligaments (Bergman et al., 1994). Further studies are needed to verify the presence of this collagen modification in the connective tissue of the PFMs and to assess its involvement in the passive properties. Most importantly, it should be pointed out that the proposed method does not allow PFM passive properties to be isolated from the vaginal and surrounding tissues.

In our protocol, the PFM passive properties were assessed in four conditions. With regard to the lengthening and shortening conditions, intra-class coefficients showed that the last three cycles were more stable and might provide more relevant information about the passive properties. This is in agreement with the force–length curves reported in peripheral joints, suggesting that the two first cycles are often non-representative of the real tissue properties (Taylor et al., 1990). Consequently, in the present study, we chose to present the data from the last three cycles.

An increase in PES and passives forces was observed with an increase in the vaginal aperture and hence, in the PFM length. Similarly for the skeletal muscles in the extremities, an increase in forces and PES is reported when a muscle is lengthened (Magnusson, 1998). Moreover, a quasi linear relationship was observed between passive forces and apertures. This differs from the nonlinear force–length relation reported in muscles of the extremities (Magnusson, 1998 and Gajdosik, 2001). Two factors may explain this divergence. First, the subjects' tolerance may not allow stretching that reaches a vaginal aperture zone where the passive forces increase dramatically. Second, the PFMs and surrounding tissues are composed of tissue with high elastic properties. Taking into account the elasticity required for vaginal delivery (Martins et al., 2007), this hypothesis of high tissue elasticity seem plausible. Furthermore, the passive forces at maximal apertures reached 8.15 N. The magnitude of the passive forces is relevant, considering that the mean maximal voluntary strength was 10.0 N. Passive forces of such importance may be involved in continence by counteracting the downward effect of intra-abdominal pressure on the urethra in the absence of PFM contraction.

In contrast to Verelst and Leivseth (2004), who assessed the PFMs only statically by increasing the vaginal diameter laterally, we applied both a static and dynamic antero-posterior stretch. This direction was chosen in view of the major orientation of levator ani muscle fibres, which run from the pubis towards the coccyx. Moreover, Constantinou et al. (2002) confirmed, using MRI, that a PFM contraction produces mainly a postero-anterior force vector and displacement. Considering that PFM passive measurement should be evaluated at maximal muscle lengthening (Gajdosik, 2001), an antero-posterior stretch was hypothesized to provide better lengthening of the muscle fibres responsible for compressing the urethra and thus maintaining continence. Therefore, we chose to evaluate the passive force in the same direction (antero-posterior) as the direction of force generated under voluntary contraction. It appears physiologically sound to impose stretching in this axis. This choice should be confirmed experimentally when differentiating between continent and incontinent women. Moreover, it is reported in rheological models (relationship between force, deformation and time) that viscous and elastic behavior is inherent in biological tissues (Magnusson, 1998). Therefore, in addition to a static stretch (muscles stretched and the forces recorded when stabilized), we applied a dynamic stress evaluating the response of the tissue in real time. This feature may be important for continence since the PFMs and surrounding structures are suddenly stretched during an increase in intra-abdominal pressure (i.e. coughing). Consequently, urethral support might depend on the stiffness of the PFMs in this short-lasting event.

Correlations between passive properties were performed to examine parameter redundancy. Since the percentage of force losses was not significantly correlated with the other parameters, they may provide different information. A significant linear relation was found between the initial passive resistance (condition #1) and the force at minimal opening (F_{Min}, condition #3). However, the initial passive resistance was related to other parameters than F_{Min}, suggesting that these parameters may not fully assess the same phenomenon. This may be explained by the nature of the stretch, static for the initial passive resistance and dynamic for the F_{Min}. The latter may be influenced by the effect of the previous stretch. Moreover, the correlation between the resistance at maximal aperture (condition #2) and the force at maximal aperture (F_{Max}, condition #3) was excellent but, unlike minimal aperture, they were related to the same parameters. The resistance at maximal aperture and F_{Max} may hence be redundant. Furthermore, no linear relationship was found between forces and PES at minimal aperture and those evaluated at maximal aperture. The differences between minimal and maximal aperture may originate from the properties assessed. Forces and PES at minimal aperture may be linked more to the vaginal configuration at rest or the urogenital size while forces and PES at maximal aperture may estimate the passive behavior when the PFMs are stretched under exertion (i.e. coughing). This interpretation is supported in part by the negative correlation between the aperture at 3.5 N ($A_{3.5\,N}$) and initial passive resistance. There is no negative correlation between the aperture at 3.5 N ($A_{3.5\,N}$) and the passive resistance at maximal aperture. Nevertheless, before completely eliminating a parameter, its capacity to discriminate between continent and stress urinary incontinent women should be assessed.

That this study was intended to present a new methodology and was therefore based on a small sample and the fact that the subjects were all physiotherapists constitute limitations to this research. The variability observed in our data may be explained by the small sample size and the heterogeneity of our sample, which ranges from young nulliparous women to middle-aged multiparous women. Our results should therefore not be generalized to normal values for women.

5. Conclusion

This is a new and original approach to evaluating the PFM passive properties. These measurements may prove useful for better understanding stress urinary incontinence patho-physiology, for evaluating the efficacy of conservative treatment and for defining the underlying changes in the PFM function following treatment. The psychometric properties of this technique applied to PFMs are currently under study.

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