UROKIN: A Software to Enhance Our Understanding of Urogenital Motion

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Abstract—Transperineal ultrasound (TPUS) allows for objective quantification of mid-sagittal urogenital mechanics, yet current practice omits dynamic motion information in favor of analyzing only a rest and a peak motion frame. This work details the development of UROKIN, a semi-automated software which calculates kinematic curves of urogenital landmark motion. A proof of concept analysis, performed using UROKIN on TPUS video recorded from 20 women with and 10 women without stress urinary incontinence (SUI) performing maximum voluntary contraction of the pelvic floor muscles. The anorectal angle and bladder neck were tracked while the motion of the pubic symphysis was used to compensate for the error incurred by TPUS probe motion during imaging. Kinematic curves of landmark motion were generated for each video and curves were smoothed, time normalized, and averaged within groups. Kinematic data yielded by the UROKIN software showed statistically significant differences between women with and without SUI in terms of magnitude and timing characteristics of the kinematic curves depicting landmark motion. Results provide insight into the ways in which UROKIN may be useful to study differences in pelvic floor muscle contraction mechanics between women with and without SUI and other pelvic floor disorders. The UROKIN software improves on methods described in the literature and provides unique capacity to further our understanding of urogenital biomechanics.

Keywords—Stress urinary incontinence, Pelvic floor muscles, Maximum voluntary contraction, Urogenital kinematics.

INTRODUCTION

Tasks involving physical exertion (e.g. coughing) cause an increase in intra-abdominal pressure (IAP); the diaphragm descends and the abdominal muscles contract, causing compression of the urogenital organs,3,17 and increasing the bladder pressure. In women with stress urinary incontinence (SUI), bladder pressure can exceed urethral closure force, resulting in urine leakage. SUI may result from concurrent failures in urethral sphincter function,5,21,22 urethral support,21,27,30 and pelvic floor muscle (PFM) mechanics,5,23,24 yet the exact combination and interaction of these phenomena is poorly understood. Currently SUI is diagnosed through the subjective report of symptoms16 with no distinctions regarding the underlying pathomechanics.

Studying the motion of urogenital landmarks, identified by dynamic sagittal plane transperineal ultrasound (TPUS), may increase our understanding of the pathomechanics associated with SUI and other pelvic floor disorders. TPUS imaging allows for inexpensive, non-invasive measurement of urogenital morphology and the mobility of relevant structures during dynamic tasks. Using TPUS, the kinematics of the anorectal angle (ARA),17,24 urethra,27,30 and bladder neck (BN)17,24 have been associated with PFM contraction,2,15,23 urethral stability,27,30 and bladder support,7,23 respectively. Differences in urogenital landmark motion between women with and without SUI have been identified in the literature.17,23,24 Unfortunately, landmark motion detected from TPUS video is vulnerable to error caused by in-plane probe motion with respect to the imaging surface (i.e. the perineum), particularly because there is only one rigid,
non-deforming landmark, the pubic symphysis (PS).\textsuperscript{29} Methodologies to correct for probe motion\textsuperscript{17,23,24} have required the capture of the complete mid-sagittal profile of the PS in addition to the ARA, which is often not possible when imaging women with elongated pelvic floors, such as those with pelvic organ prolapse.\textsuperscript{14} Despite these limitations, features of urogenital kinematics derived from TPUS have demonstrated high levels of reliability.\textsuperscript{26}

Urogenital kinematic curves may contribute valuable information to our understanding of the pathomechanics of pelvic floor disorders, including SUI. This study aimed to present UROKIN, a semi-automated software developed to compensate for in-plane probe motion in order to provide a valid means of quantifying sagittal plane urogenital kinematics when the PS is only partially visible. Here, we hypothesized that features of urogenital kinematic curves generated by the UROKIN software using data acquired during maximum voluntary PFM contraction would be significantly different between women with and without SUI, thus demonstrating the potential utility of the software.

**MATERIALS AND METHODS**

**Participants**

A secondary analysis of data from an ongoing study was approved by the University of Ottawa Health Science and Sciences, the Queen’s University Health Sciences, and Affiliated Teaching Hospitals’ Research Ethics Boards. Twenty women reporting symptoms of SUI and who were on a waiting list for mid-urethral sling surgery were referred from clinics in Kingston and Ottawa, Canada. A convenience sample of 10 women with no history of urogenital symptoms was recruited from the local community to serve as a control group. Exclusion criteria for both groups were: fecal incontinence, pregnancy or being less than 1 year post-partum at the time of recruitment, anterior pelvic organ prolapse greater than ICS POP-Q stage II,\textsuperscript{25} any posterior compartment prolapse, use of medications known to increase or relieve incontinence, known neurological or connective tissue disorders, and self-reported urge incontinence. Symptomatic participants underwent a standardized 30-min pad test to evaluate the severity of SUI\textsuperscript{21} and filled out the ICIQ-FLUTS questionnaire to assess lower urinary tract symptoms.\textsuperscript{1}

**Experimental Protocol**

Participants underwent a clinical examination: digital palpation was used to rule out significant pelvic mass and sensation or reflex abnormalities reflective of neurological impairment. PFM strength and function were scored using the Modified Oxford Scale (MOS) and the PERFECT scheme, respectively.\textsuperscript{16} With participants in the lithotomy position, TPUS imaging was performed using a GE Voluson-i (GE Healthcare Austria GmbH & Co OG, Zipf, Austria) in 2D real-time B-mode and a curvilinear probe (RAB 4–8 MHz) with the acquisition angle at its maximum of 85°. The probe was covered with ultrasound gel, a condom, and more gel. As a part of a larger protocol, the study physical therapist acquired dynamic TPUS video of three repetitions of a maximum-effort voluntary contraction (MVC) of the PFMs. MVCs were conducted with standardized encouragement to increase the level of contraction until no further motion of the ARA or urethra was seen for at least one second on the ultrasound image pane, at which time the participant was instructed to relax. Subsequently, women were imaged during three more PFM MVCs while volumes of the levator hiatus were acquired in 4D.\textsuperscript{6}

**Image Analysis**

Computational methods were implemented using the UROKIN interface, (MATLAB 2015b; Mathworks, Natick, MA, USA). For each trial, an initial reference frame was selected in which the posterior margin of the PS was traced (Fig. 1a). This trace was subsequently duplicated across all video frames and maximally aligned in each frame with the PS, as seen by the user. UROKIN generated a global coordinate system (GCS) in the reference frame, and a local coordinate system (LCS) in each consecutive frame using the profile of the PS (Fig. 1b). A transformation matrix (TR) was constructed in each frame using the global \((I,J,K)\) and local \((i,j,k)\) unit vectors, as in Eq. (1), where \((p, q)\) represents the \(x\) and \(y\) distances between the origins of the GCS and LCS. Using TR, any local landmark can be converted to the GCS as in Eq. (2), where \((x', y')\) represents the local position of a point and \((x, y)\) is that same point in the GCS.

\[
TR = \begin{bmatrix}
i \cdot I & i \cdot J & p \\
j \cdot I & j \cdot J & q \\
0 & 0 & 1
\end{bmatrix}
\] (1)

\[
x' = \begin{bmatrix}i \cdot I & i \cdot J & p \\
j \cdot I & j \cdot J & q \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}x \\
y \\
1
\end{bmatrix}
\] (2)

The user then identified the local positions of all relevant landmarks which were subsequently converted
to the GCS, eliminating error from in-plane probe motion. All trajectories were automatically calculated, as in Eq. (3). In this scenario, the ARA displacement at time \( i \), represented by \( ARA_{disp}(i) \), is equal to the difference between the ARA’s position at time \( i \), \( p(i) \), and time \( 1 \), \( p(1) \). Velocities and accelerations were determined using the first and second time derivatives of displacements.

\[
ARAdisp(i) = p(i) - p(1)
\]  

Drawing on standard practice in human gait biomechanics, where stride frequency is approximately 1 Hz and 99.7% of the signal power exists below 6 Hz, we computed the maximum frequency of the MVC contraction across all patients and trials to be 0.45 Hz. We theorized that a similar percentage of signal power would be below 6 Hz for our application, as well. Based on the Nyquist theorem, the minimum sampling rate for TPUS data should be 12 Hz to avoid aliasing. The minimum frame rate across our sample was 28 Hz, which is adequate to avoid aliasing. We smoothed our trajectories using a dual pass, low pass, 2nd order Butterworth filter with the cut-off frequency set to the image acquisition rate (Fig. 2).

Separately, 4D volumes were analyzed based on Dietz et al. to check for the presence of a complete levator avulsion, as such a defect may impact PFM function.

### Data Analysis

Kinematic curves were time normalized from maximal levator plate (LP) length to 90% of the minimal LP length, as LP shortening is thought to reflect PFM contraction and ARA motion was increasingly variable as LP length approached its minimum. Time-normalized curves were ensemble averaged across each participant.
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ARA AP Displacement vs MOS

\( \rho = 0.64 \)

BN AP Displacement vs MOS

\( \rho = 0.30 \)

ARA CC Displacement Timing vs MOS

\( \rho = 0.43 \)

BN CC Displacement vs MOS

\( \rho = 0.30 \)

ARA AP Acceleration vs MOS

\( \rho = 0.34 \)

BN AP Acceleration Timing vs MOS

\( \rho = 0.35 \)
group. From the individual kinematic curves, the peak values and peak-timings were calculated for each variable. These variables were tested for normality (Shapiro-Wilks test), compared between groups using Student’s t-tests or Wilcoxon rank sum test ($a = 0.05$), and tested for correlation with PFM strength using Spearman’s rho ($r_s$).

**RESULTS**

There were no significant differences between groups in age (Control = 40 ± 12 years; SUI = 47 ± 10 years; $r_s = -0.13; p > 0.05$) or body mass index (Control = 23 ± 2 kg/m$^2$; SUI = 26 ± 5 kg/m$^2$; $r_s = -0.06; p > 0.05$), however women with SUI had higher parity than those without SUI (Control = 1±1; SUI = 3±1; $p = 0.003$) and parity correlated significantly with PFM strength ($r_s = -0.47; p < 0.01$). The control group demonstrated greater PFM strength (Control = 4.4 ± 0.4; SUI = 3.0 ± 0.6; $p < 0.001$) on MOS and higher PFM function (Control = 18.7 ± 2.8; SUI = 13.7 ± 3.0; $p < 0.001$) on the PERFECT scheme, which also correlated significantly with MOS ($r_s = 0.56; p < 0.001$). ARA and BN kinematic peaks and peak-timings exhibiting the highest correlations with MOS evaluation of PFM strength are shown in Fig. 3. Women with SUI scored an average of 12.9 ± 3.7 on the ICIQ-FLUTS in subjective report of lower urinary tract symptoms.

Levator avulsions were observed in four women, who were all part of the SUI group. The women with avulsion exhibited kinematic peaks and peak timings that were well within the means and standard deviations computed for the group as a whole (Fig. 3).

The ARA and BN kinematic curves are shown in Figs. 4 and 5, respectively. No significant differences were found between groups in the posterior or caudal kinematic peaks or peak-timings. The control group exhibited higher peak anterior displacement ($p < 0.01$) and later timing of the peak cranial displacement ($p < 0.01$) of the ARA (Table 1). Peak cranial displacement of the BN was higher in the control group ($p < 0.05$). ARA peak anterior displacement ($r_s = 0.65, p < 0.001$), cranial displacement peak-timing ($r_s = 0.48, p < 0.01$), and peak anterior acceleration ($r_s = 0.39, p < 0.05$) all correlated moderately with PFM strength. BN kinematics did not correlate with PFM strength.
FIGURE 5. Preliminary analysis by the UROKIN software comparing bladder neck kinematics in 20 women with SUI (red) and 10 healthy control participants (green), during maximum voluntary contractions of the pelvic floor muscles from 0 to 90% of the peak shortening of the levator plate. Polar plots compare the average displacements (a) and accelerations (b) of the bladder neck in 2D. Cranial-caudal displacements (b) and accelerations (e) and the anterior–posterior displacements (c) and accelerations (f) show the decomposed kinematics of the bladder neck. Shaded bars show standard error.

TABLE 1. Peak and timing of the anorectal angle (ARA) and bladder neck (BN) displacements and accelerations in the anterior–posterior and cranial-caudal directions during a maximum voluntary pelvic floor muscle contraction performed by women with and without (control) stress urinary incontinence (SUI).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control (n = 10)</th>
<th>SUI (n = 20)</th>
<th>Spearman’s rho</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Displacement</td>
<td>Anterior–posterior</td>
<td>Peak (mm) 11.7 ± 0.8*</td>
<td>7.6 ± 0.7*</td>
</tr>
<tr>
<td></td>
<td>Timing (%) 90.0 ± 0.0</td>
<td>90.0 ± 0.0</td>
<td>NA</td>
</tr>
<tr>
<td>Cranial–caudal</td>
<td>Peak (mm) 2.2 ± 0.5</td>
<td>2.2 ± 0.4</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Timing (%) 71.5 ± 9.6*</td>
<td>55.8 ± 7.1*</td>
<td>0.43*</td>
</tr>
<tr>
<td>Acceleration</td>
<td>Anterior–posterior</td>
<td>Peak (mm/s²) 89.5 ± 19.0</td>
<td>57.8 ± 6.4</td>
</tr>
<tr>
<td></td>
<td>Timing (%) 17.5 ± 2.7</td>
<td>18.1 ± 2.1</td>
<td>0.09</td>
</tr>
<tr>
<td>Cranial–caudal</td>
<td>Peak (mm/s²) 28.1 ± 8.0</td>
<td>29.9 ± 5.3</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>Timing (%) 25.3 ± 4.9</td>
<td>31.4 ± 6.1</td>
<td>− 0.03</td>
</tr>
<tr>
<td>BN</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Displacement</td>
<td>Anterior–posterior</td>
<td>Peak (mm) 4.9 ± 0.6</td>
<td>4.0 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>Timing (%) 90.0 ± 0.0</td>
<td>88.8 ± 1.1</td>
<td>− 0.07</td>
</tr>
<tr>
<td>Cranial–caudal</td>
<td>Peak (mm) 2.4 ± 0.5*</td>
<td>1.4 ± 0.3*</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>Timing (%) 79.6 ± 9.9</td>
<td>75.3 ± 5.2</td>
<td>0.05</td>
</tr>
<tr>
<td>Acceleration</td>
<td>Anterior–posterior</td>
<td>Peak (mm/s²) 42.1 ± 9.0</td>
<td>32.2 ± 4.6</td>
</tr>
<tr>
<td></td>
<td>Timing (%) 20.9 ± 3.9</td>
<td>14.1 ± 2.1</td>
<td>0.35</td>
</tr>
<tr>
<td>Cranial–caudal</td>
<td>Peak (mm/s²) 20.4 ± 4.6</td>
<td>13.5 ± 2.3</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Timing (%) 19.3 ± 3.9</td>
<td>17.0 ± 3.7</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Kinematic data are presented from 0 to 90% of the maximum shortening of the levator plate. Spearman’s rho measures the correlation between the given variable and the manually assessed pelvic floor muscle (PFM) strength across all participants. Significant group differences are indicated by * and significant correlations with PFM strength are indicated by $^{*W}$. 

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DISCUSSION

The motion of urogenital landmarks, measured using TPUS, has contributed to our understanding of the role of the PFMs in providing structural support, limiting urethral displacement and enabling the force transmission necessary for urethral closure. Relative to women with SUI, our control group demonstrated larger anterior ARA displacement, increased duration in cranial ARA displacement, and larger cranial BN displacement during PFM MVC. These findings are consistent with the significantly higher PFM strength seen in the control group relative to the SUI group and demonstrate that the UROKIN software has the potential to enhance our understanding of urogenital kinematics and pathomechanics associated with different disorders of the pelvic floor.

Indeed, differences in the patterns of urogenital kinematics between women with and without SUI seen in this study may relate to the lower PFM strength seen in the women with SUI. However, given that the women with SUI in this study had higher parity than the women without SUI, the differences seen here may also be associated with parity, which has been shown independently to influence urethral mobility. Further, we presented data recorded during voluntary contractions and therefore the results do not reflect the capacity to stabilize the urethra during functional tasks that normally result in incontinence, such as coughing or sneezing. There are likely multivariate associations among PFM strength, pelvic support, urethral support and urethral sphincter function that are implicated in SUI.

In our analysis of PFM contractions, while aspects of ARA kinematics correlated significantly with PFM strength, BN motion did not. This difference was likely due to the connective tissues attenuating the force transmission of the PFM contraction on the bladder and urethra. These findings are consistent with the literature which shows measures of BN displacement are the highest in women with substantial urethral mobility, likely because a given PFM contraction will move highly elastic distended tissues much further than stiff tissues.

Studies of sagittal plane urogenital kinematics have shown that women with SUI experience initial posterior ARA motion during coughing whereas healthy controls exhibit initial anterior displacement of the ARA. During a cough, diaphragmatic expansion and abdominal contraction cause an increase in IAP that is not present during a PFM MVC, yet our results are complementary. In our SUI group, PFM contraction was unable to generate the magnitude of anterior ARA motion, nor sustain the cranial ARA motion to the extent seen in the control group. Additionally, women with SUI exhibited less cranial BN displacement than the control group, however, in both cases, this motion was quite small at 2.4 and 1.4 mm, respectively. These results may suggest that the capacity to generate and maintain cranial displacement of the pelvic structures through PFM contraction may be an important feature in the pathomechanics of SUI.

It is important to recognize that kinematic curves of urogenital landmark motion are artifacts of PFM contraction, and differences observed between women with and without SUI may indicate differences in strength, neuromuscular control, and/or tissue morphology between groups. Although palpation is not an ideal means of evaluating PFM force generating capacity, we found that women with SUI exhibited weaker PFMs than the control group. Further, PFM strength was moderately correlated with peak anterior displacement of the ARA and with the timing of the peak cranial displacement of the ARA. The literature has suggested that some women with SUI demonstrate differences in motor control compared to women without SUI. Specifically, they appear to co-contract their abdominal muscles during PFM MVCs, which would raise the IAP and could consequently limit the cranial displacement of the ARA and BN.

Although UROKIN shows promise in enhancing our understanding of the pathomechanics of SUI, urogenital kinematic analysis should not be used in isolation. Differences in the motion of the ARA and BN during PFM contraction may be influenced by defects in the connective tissues. For example, levator avulsion or connective tissue proliferation may limit the extent of the anterior displacement of the ARA during PFM contraction despite adequate neuromuscular activation of the PFMs. In the current study, we evaluated the presence/absence of levator avulsions using 4D ultrasound imaging, and detected complete unilateral avulsion in four of the 20 participants with SUI. Although the kinematic peaks and peak-timings for women with levator avulsions remained in line with those of the women in the SUI group as a whole (Fig. 3), suggesting that urethral kinematics may not be impacted by unilateral levator avulsion. However, based on the sample size and characteristics, we did not formally evaluate the impact of levator avulsion on urogenital kinematics here.

The women in this study were taught by an experienced pelvic floor physiotherapist to correctly contract their PFMs prior to ultrasound data collection, meaning that they were instructed to generate a squeezing and a lift of the levator hiatus in the absence of bracing with the abdominal or gluteal muscles and without bearing down. Trials in which women appeared to contract their abdominal or hip musculature prior to activating their PFMs, or in excess of
what is normally apparent, were redone. That said, the abdominal muscles appear to work in synergy with the PFMs and it does not appear to be possible to maximally activate the PFMs without some degree of abdominal muscle co-contraction. Abdominal muscle contraction increases intra-abdominal pressure, which, in turn, likely limits the cranial motion of the bladder neck during PFM contraction. The use of electromyography during the ultrasound imaging procedure used here would help to elucidate the impact of differences in motor control on the urogenital kinematics computed using UROKIN and warrants consideration now that this proof of concept is complete.

Further investigation is needed to understand the differences in urogenital kinematics between women with and without different pelvic floor disorders, during the performance of different tasks, and stratified by risk factors (e.g., vaginal delivery) and morphologic features (e.g., type and stage of prolapse, hiatal ballooning, avulsion). With the UROKIN software now developed, such investigations are possible. Moving forward, this work would benefit from incorporating concurrent analyses such as intravaginal dynamometry, urodynamics, and patient oriented outcomes.

As with any research, there are limitations to this study. Alignment of the coordinate systems with the anatomical planes is difficult since the probe position and pelvic position cannot be standardized nor restricted. During image acquisition, the orientation of the probe must be adjusted to optimize image quality while retaining the relevant landmarks within the field of view. This can be challenging, especially when landmarks can move out of the imaging plane, as may be the case with unilateral injury or scar tissue. Additionally, the extent of user-input currently required to generate outcomes using the UROKIN software makes image analysis very time intensive. Based on the promising results obtained here, we are working to automate the image segmentation and to determine the minimum sampling rate required to optimize efficiency while avoiding aliasing during different functional tasks.

Further, as noted above, the strict exclusion criteria, sample characteristics and task studied limit the generalizability of our findings. No attempt was made here to match the small samples on parity, vaginal delivery, or evidence of levator trauma, which may have influenced the outcomes obtained. Indeed, parity is a major risk factor for SUI, yet the precise mechanism underlying this association is not known, with connective tissue strain, tear, or levator ani or urethral sphincter denervation all being possibilities. While levator defects are not associated with symptoms of bladder dysfunction or risk of SUI, levator avulsion has been associated with lower PFM strength, as measured by MOS and PFM activation is highly correlated with urogenital landmark motion measured by TPUS. Based on this proof of concept, we may now move forward to investigate the impact of different risk factors or known impairments on the sagittal plane urogenital kinematics of women. Expanding this software to 3D would also eliminate limitations associated with landmarks moving out of the mid-sagittal plane.

**CONCLUSIONS**

The UROKIN software provides the capacity to gain significant insight into normal PFM mechanics, and pathomechanics associated with different disorders involving the pelvic floor including incontinence, pelvic organ prolapse, urine retention, chronic constipation and dyspareunia. Research has shown that underlying morphological or pathomechanical factors may be relevant in the selection of successful interventions for women with SUI. Women exhibiting strong PFMs and urethral hypermobility are less likely to benefit from PFM training. Additionally, women with smaller urethral cross-sectional areas are less likely to see improvement with mid-urethral sling insertion and would perhaps be more likely benefit from PFM training or the use of urethral bulking agents. A better understanding of urogenital kinematics, measured during dynamic tasks, may provide the insight needed to better direct care recommendations.

Despite its current limitations, the UROKIN software allows for complete analysis of 2D urogenital kinematics and can identify significant differences between women with and without SUI. Further, the UROKIN outcomes are logical in the context of published clinical findings. The UROKIN software yields improved functionality for more complex analysis than has been used to date to aid in our understanding of urogenital biomechanics.

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