Segmentation of Pelvic Organs and Muscles on Axial T2-weighted MR Images of Female Pelvic Cavity

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Outline:

- **Introduction**
  - Research backgrounds
  - Geometric deformable models

- **Algorithm**
  - Segmentation of the pelvic organs
  - Segmentation of the levator ani muscle

- **Analysis & Discussions**

- **Conclusion**
Introduction

Motivation

Study of Pelvic Floor Dysfunctions

Pelvic floor dysfunctions are a series of diseases such as urinary incontinence, fecal incontinence, pelvic organ prolapse, etc., which are affecting a large population of women, especially older women.

30–50% of women in Europe & USA are affected by urinary incontinence;* 11%–15% of population of New Zealand & 2.2–6.9% of population of the USA suffer from fecal incontinence #


Introduction

- **Motivation**

Patient-specific Study

- identify the anatomy
- build 3D models
- quantitative analysis
- biomechanical analysis
- therapeutic planning

The first step is to segment the relevant pelvic structures from the acquired images.
Introduction

- Objective

One of the major concerns is the relationship between the pelvic organs and the pelvic floor muscles.

Segmentation of Pelvic Structures

- Pelvic organs
  - Three pelvic organs that are frequently involved in the pelvic floor dysfunctions are Bladder, Vagina, and Rectum.

- Pelvic floor muscles
  - Levator ani muscles
Introduction

Objective – why the axial T2-weighted MR images

Magnetic resonance imaging is a preferred imaging modality for this study because it can provide static high imaging quality of the soft tissues. The pelvic structures can be better identified on the T2-weighted MR images than on the T1-weighted MR images; compared with the sagittal view and coronal view, the anatomy of pelvic structures is more clearly presented on the axial plane.
Anatomy

- **In axial plane**

- Bladder sits inferior to the uterus and anterior to the vagina; at the topside in the axial plan
- Vagina locates in front of the rectum and behind the bladder; between the bladder and rectum
- Rectum is continuous inferiorly with the anal canal; above the levator ani muscles
- Levator ani muscle supports the pelvic organs; at the downside in the axial plane
Anatomy

- Imaging appearances

2D TSE sequence with field strength: 1.5 T, TE: 103 ms, TR: 5239 ms, bandwidth: 130 Hz/pixel, FOV: 220×220 mm². Acquired from a 68 years old woman.

2D TSE sequence with field strength: 1.5 T, TE: 98 ms, TR: 3980 ms, bandwidth: 130 Hz/pixel, FOV: 256×220 mm². Acquired from a 20 years old woman.
Introduction

- **Segmentation of pelvic cavity— a challenging problem**

  The complex anatomy and relationship between the pelvic organs and muscles and their variable shape deformation make the pelvic cavity the one of the most delicate parts of human body.
Geometric deformable models

- **Segmentation through contour movement**

The key point is to define a moving equation following which the contours can move to the object boundary and be attached there.

\[ \frac{\partial \phi}{\partial t} + F |\nabla \phi| = 0 \]

Definition of the speed function

With the level set method*, geometric deformable models are capable of segmenting structures with complex topology and can easily handle the topological changes during the movement.

Imaging Appearance on T2-weighted MR images

- **Bladder**
  - the bladder lumen has high signal intensities, but the bladder wall has low signal intensity that is similar to the muscular layers of vagina and rectum

- **Vagina**
  - a strip in the axial plane, has medium signal intensity, may have a high signal intensity center due to the hormonal stimulation

- **Rectum**
  - layers can be well depicted. The muscular layer has different appearance to bladder & vagina; the rectal lumen has low signal intensities similar to the muscular layer of the vagina

- **Levator ani muscles**
  - normally thin strip with “V” shape & the shape has large variations; status closely related with the pelvic organs
Algorithm

- **Organs** - comparison between appearance & prior shape knowledge

A modified region competition algorithm proposed by Brox & Weickert, 2006

\[
\begin{align*}
\frac{\partial \phi_1}{\partial t} &= \delta(\phi_1) \left( p_1 (e_1 - \max(e_2, e_3, e_1 - 1)) + \alpha \nabla p_1 \cdot \nabla \phi_1 + \gamma_1 \text{div} \left( \frac{\nabla \phi_1}{|\nabla \phi_1|} \right) \right) \\
\frac{\partial \phi_2}{\partial t} &= \delta(\phi_2) \left( p_2 (e_2 - \max(e_1, e_3, e_2 - 1)) + \beta S_r + \gamma_2 \text{div} \left( \frac{\nabla \phi_2}{|\nabla \phi_2|} \right) \right) \\
\frac{\partial \phi_3}{\partial t} &= \delta(\phi_3) \left( \max(p_2, p_3) \cdot (e_3 - \max(e_1, e_3 - 1)) + \nu S_r + \gamma_3 \text{div} \left( \frac{\nabla \phi_3}{|\nabla \phi_3|} \right) \right)
\end{align*}
\]

\[e_k = \log p_k\], where \(p\) is the probability density function

---


Moving equation

- Bladder

The surrounding tissues around the bladder have similar appearance as the vagina and rectum.

White: an expanding speed
Black: a contracting speed

To prevent leakage

Appearance comparison with the vagina and rectum

\[ \frac{\partial \phi_1}{\partial t} = \delta(\phi_1) \left( p_1 (e_1 - \max(e_2, e_3, e_1 - 1)) + \alpha \nabla p_1 \cdot \nabla \phi_1 + \gamma_1 \text{div} \left( \frac{\nabla \phi_1}{|\nabla \phi_1|} \right) \right) \]

Item to stick the contour on the boundary

\[ p_1 (e_1 - \max(e_2, e_3, e_1 - 1)) < p_1 \log p_1 \to 0 \quad \text{when} \quad p_1 \to 0 \]

\[ e_k = \log p_k \]
Moving equation

- Vagina

To prevent the incompleteness and the leakage

\[
\frac{\partial \phi_2}{\partial t} = \delta(\phi_2) \left[ p_2 \left( e_2 - \max(e_1, e_3, e_2 - 1) \right) + \beta S_v + \gamma_2 \text{div} \left( \frac{\nabla \phi_2}{|\nabla \phi_2|} \right) \right]
\]

To prevent leakage

Appearance comparison with the bladder and rectum

Item derived from prior shape item to avoid inner boundary and incomplete segmentation on caused by noise

\[
S_v = - \left( H \phi_2(x) - H \phi_2(x - \mu_{\phi_2}) \right) - \frac{(x - \mu_{\phi_2})^T}{\int H \phi_2 dx} \times \int \left( H \phi_2(x') - H \phi_2(x' - \mu_{\phi_2}) \right) \delta \phi_2(x') \nabla \phi_2(x') dx'
\]
Moving equation

1. **Rectum**

   To get the correct outer boundary

   \[
   \frac{\partial \phi_3}{\partial t} = \delta(\phi_3) \left( \max(p_2, p_3) \right) \left( e_3 - \max(e_1, e_2, 1) \right) + \nu S_r + \gamma_3 \text{div} \left( \frac{\nabla \phi_3}{|\nabla \phi_3|} \right)
   \]

   To prevent leakage

   Comparison with the bladder

   Shape priori item to avoid inner boundary caused by rectal lumen

   \[
   S_r = - \left( H \phi_3(x) - H \phi_3(x - \mu_\phi) \right) - \frac{(x - \mu_\phi)^T}{\int H \phi_3 \, dx} \times \int \left( H \phi_3(x') - H \phi_3(x' - \mu_\phi) \right) \delta \phi_3(x') \nabla \phi_3(x') \, dx'
   \]
Segmentation Example

Geodesic Active Contour

Proposed Approach
Segmentation Example II

Segmentations of the pelvic organs simultaneously
Algorithms – Bladder

The coupling approach requires the simultaneous appearances of the three pelvic organs. When the segmentation only concerns on a specific pelvic organ, this algorithms may not be applicable. Plus, sometimes a single inner /outer boundary of the pelvic structure is not enough.

Our recent work focuses on the segmentation of the urinary bladder. The application requires the segmentation of both the inner and the outer boundaries of the bladder. The two boundaries are needed to build the 3D model of the bladder wall and evaluate its thickness and other geometric features.
Algorithms – Bladder

The difficult part is to segment the outer boundary of the bladder wall due to the complex imaging background.
Algorithms – Bladder

Segmentation using geodesic active contour: Left: incomplete segmentation; middle: inner boundaries. Right: the leakage problem of using large constant speed to pass the inner boundary.

\[ g = \frac{1}{1 + |\nabla G_\sigma \ast I|^p} \]

Sensitive to noise and intensity variations, and may cause **inner boundaries** or **leakage** (decreased intensity gradient caused by partial volume effect)

Parameter selection is problematic.
Algorithms – Inner boundary

- **Segmentation**

  Moving equation: intensity statistics

  \[
  \frac{\partial \phi}{\partial t} = p(I)(1+\kappa)|\nabla \phi| + \lambda \nabla p(I) \cdot \nabla \phi
  \]

  Main external force:
  Region-based expanding speed

  To accelerate the movement and help to stick the contour on the boundary

  \[
  g(I) = p(I) = \frac{1}{\sqrt{2\pi} \sigma^*} \exp \left( -\frac{(I - \mu)^2}{2\sigma^*^2} \right)
  \]

  When the intensity varies in the normal range, the speed value changes smoothly; when the intensity is beyond the normal range, the speed decreases quickly.

  \[
  g(I) \in [0,1]
  \]

  Region-based

  \[
  \sigma^* = \max \left( \sqrt{\frac{\int_{\Omega} H(\phi(x,y))(I(x,y) - \mu)^2 \, dx \, dy}{\int_{\Omega} H(\phi(x,y)) \, dx \, dy}}, \sigma_0 \right)
  \]

Algorithms – Outer boundary

ROI & Initial contour

ROI: \( \Omega_0 = \{ p = (x, y) \mid 0 \leq D(p, C_0) \leq D_{\text{max}} \} \)

Initial contour:
\( L_0 = \{ p = (x, y) \mid p \in \Omega_0, \ D(p, C_0) = D_{\text{max}} - \varepsilon \} \)

\( C_0 \) is the boundary of rectum; \( D_{\text{max}} \) is the thresholds; \( D \) is the distance function defined as

\[
D(p, C_0) = \begin{cases} 
\min_{p_0 \in C_0} d(p, p_0), & p \text{ is outside } C_0 \\
-\min_{p_0 \in C_0} d(p, p_0), & p \text{ is inside } C_0
\end{cases}
\]

ROI should:
- have a simple background
- cover the bladder wall completely

A suitable model is the Chan-Vese model based on the appearance of the bladder wall
When the bladder is distended, the appearance of the bladder wall is frequently blurred and some parts may even become invisible due to the diffusion. Consequently, the outer boundary segmented by the C-V model may cross the outer boundary and overlap with the inner boundary.
Algorithms – Outer boundary

Shape influence field

A force is needed to keep the two boundaries separated. The blurred parts of the outer boundary can be inferred based on three factors: smoothness, bladder wall thickness, and similarity between the shapes of inner and outer boundaries.

\[
S(x, y) = \frac{1 + \alpha \kappa_0}{(D(p, C_0) - 1/r)^2 + \varepsilon} \cdot \bar{n}_0, \quad p = (x, y) \in \Omega_0
\]

1mm is assumed as the minimum thickness of the bladder wall; 1/r maps the distance to the pixel distance on the image

where \( \alpha \) is a parameter. \( D(p, C_0) \) is the distance between the point \( p \) and the curve \( C_0 \). \( \kappa_0 \) and \( n_0 \) are the curvature and the outward normal vector at the point \( p_0 \) which belongs to \( C_0 \) and satisfies \( d(p, p_0) = D(p, C_0) \).

Spatial distribution of the Shape Influence field. The influence of this field increases when the contour moves to the outer boundary. The large field at the places around 1mm to the inner boundary will prevent further moving of the contour. Hence, the field can avoid overlapping.
**Algorithms – Outer boundary**

- **Segmentation:**
  
  Moving equation#: appearance + shape influence

  \[
  \frac{\partial \phi}{\partial t} = \mu \cdot \text{div} \left( \frac{\nabla \phi}{|\nabla \phi|} \right) - \lambda_1 \left( I(x, y) - c_1^* \right)^2 + \lambda_2 \left( I(x, y) - c_2 \right)^2 + S(x, y) \cdot \nabla \phi
  \]

  - **Internal force:** Curvature
  - **External force:** Imaging appearance

  where \( \Phi \) is the signed distance function; \( \mu, \lambda_1, \lambda_2 \) are the parameters; \( c_1^* \) is the priori average intensity value of the levator ani; \( c_2 \) is the average intensity of the region outside the moving contour; \( S(x, y) \) is the shape influence field.

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Segmentation Procedure

Inner boundary

1. place the initial contour inside the bladder lumen
2. the inner boundary segmented by the modified geodesic active contour
3. form the ROI, the initial contour, and the shape influence field

Outer boundary

4. the outer boundary segmented by the shape-guided C-V model
Algorithm

- Levator ani muscles

  - Large shape variations along with the positions
  - May appear as pixel clusters & appearance is usually influenced by noise, and partial volume effect
  - Inhomogeneous intensity distribution under complex backgrounds
  - Below the rectum and has an arch shape
  - Shapes are related with the status of the supported organs

With the boundary of the rectum we have a guidance
Algorithm

○ Region of interest (ROI)

\[ \Omega_0 := \left\{ p = (x, y) \mid D_{\min} \leq D(p, C_0) \leq D_{\max}, \quad y \geq y_0 - y_{\text{const}} \right\} \]

\[ \Omega_0 := \left\{ p = (x, y) \mid a_0 x^2 + b_0 x + c_{\min} \leq y \leq a_0 x^2 + b_0 x + c_{\max}, \quad D(p, C_0) \geq D_{\min}, \quad y_{\min} \leq y \leq y_{\max} \right\} \]

C_0 is the boundary of rectum; y_0: average value of vertical coordinates of the boundary of rectum. D: distance function

Priori knowledge: the boundary of rectum

A proper ROI should:
- have a simple background
- cover the levator ani muscles completely

Boundary of rectum & the initial contour
Algorithm

- **Levator ani muscles**

  The levator ani are the darkest in the ROI & may appear as pixel clusters

  Two-phase segmentation

  Chan-Vese model

  Can be seen as a special case when the intensity follows the Gaussian distribution function and the variances of the internal region and external region are equal

  \[
  E = \mu \cdot \text{Length}(C) + \nu \cdot \text{Area}(\text{inside}(C)) + \\
  \lambda_1 \int_{\text{inside}(C)} |I(x, y) - c_1|^2 \, dx \, dy + \\
  \lambda_2 \int_{\text{outside}(C)} |I(x, y) - c_2|^2 \, dx \, dy ,
  \]

  \[
  \frac{\partial \phi}{\partial t} = \delta_\varepsilon(\phi) \left[ \mu \text{div} \left( \frac{\nabla \phi}{|\nabla \phi|} \right) - \nu - \lambda_1 (I(x, y) - c_1)^2 \\
  + \lambda_2 (I(x, y) - c_2)^2 \right], \text{ in } \Omega \times (0, \infty)
  \]
Algorithm

- **Shape influence field**

Inside the computational region, the levator ani are the darkest, while the connective tissues have similar appearances. Using Chan-Vese model cannot distinguish the two structures.

**Shape of rectum ↔ Shape of Levator ani**

Shape guided field is defined as:

\[ F(x, y) = \frac{1 + \alpha \kappa_0}{D(p, C)} \cdot \hat{n}_0, p = (x, y) \in \Omega_0 \]

where \( \alpha \) is a parameter, \( D(p, C_0) \) is the distance between the point \( p \) and the curve \( C_0 \), \( \kappa_0 \) and \( \hat{n}_0 \) are the curvature and the outward normal vector at the point \( p_0 \) which belongs to \( C_0 \) and satisfies \( d(p, p_0) = D(p, C_0) \).
Moving equation

- Levator ani muscles

\[
\frac{\partial \phi}{\partial t} = \delta(\phi) [\mu \text{div} \left( \frac{\nabla \phi}{|\nabla \phi|} \right) - \lambda_1 (I(x, y) - c_0)^2 + \lambda_2 (I(x, y) - c_2)^2 - \beta F(x, y) \cdot \nabla \phi], \text{in } \Omega_0 \times (0, \infty)
\]

average intensity inside the contour \(c_1\) \(\rightarrow\) \(c_0\) a priori constant

where \(\Phi\) is the signed distance function; \(\mu\), \(\beta\), \(\lambda_1, \lambda_2\) are the parameters; \(c_0\) is the priori average intensity value of the levator ani; \(c_2\) is the average intensity of the region outside the moving contour; \(F(x, y)\) is the shape influence field. \(\Omega_0\) is the computational region

Keep the integrity and topology \(\rightarrow\) Add strategy to preserve topology

Bertrand’s digital topology theory *

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Experiments

Segmentation results when the partial volume effect is appreciable:
(a) without shape influence; (b) with shape influence
Experiments II

Segmentation results when the partial volume effect is appreciable:
(c) without shape influence; (d) with shape influence
Experiments III

Segmentations of the levator ani muscles when the partial volume effect is not appreciable
## Analysis

<table>
<thead>
<tr>
<th>Imaging Features</th>
<th>Segmentation Clues</th>
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</thead>
<tbody>
<tr>
<td><strong>Pelvic Organs</strong></td>
<td></td>
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</tbody>
</table>
| - The difference between the imaging appearances of bladder lumen, the bladder wall, and the perivesical fat. The differences between the imaging appearances of the vagina and rectum with their surrounding tissues.  
- The constant shapes of the vagina and rectum | - The similarities and differences between the different layers of pelvic organs  
- Shape constrain on the vagina and rectum |
| **Levator Ani Muscles** |                  |
| The imaging appearances of the connective tissues between the muscles and the rectum | - The rectum boundary  
- Shape influence field |
### Analysis

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Pros</th>
<th>Cons</th>
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</thead>
<tbody>
<tr>
<td>Pelvic Organs</td>
<td>- Effective segmentation under complex imaging background</td>
<td>- Require simultaneous appearance of the three pelvic organs</td>
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<td></td>
<td>- Less sensitive to the influence of noise and partial volume effect due to the incorporation of level set method</td>
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<td></td>
<td>- Prior knowledge to assist the segmentation</td>
<td></td>
</tr>
<tr>
<td>Levator Ani Muscles</td>
<td></td>
<td>- Depends on the accuracy of the rectum boundary</td>
</tr>
</tbody>
</table>
## Analysis

<table>
<thead>
<tr>
<th>Segment Clues</th>
<th>Pros &amp; Cons</th>
</tr>
</thead>
</table>
| **Inner Boundary** | The large contrast between the imaging appearances of the bladder lumen and the bladder wall | - Less sensitive to the influence of noise and intensity variation; and can prevent leakage caused by the partial volume effect  
- May cause unsatisfied results when the intensity variation inside the bladder lumen is too large (e.g. the patient suffers from bladder tumor or carcinoma) |
| **Outer Boundary** | The inner boundary of the bladder | - Less sensitive to the influence of noise and intensity variation; and can prevent overlap using the shape influence field  
- Relies on the correctness of the inner boundary. May require manual intervention to avoid the influence of neighboring structures |
| The different appearances between the bladder wall and the background in the ROI | |
Conclusion

- Medical image segmentation is application-based, which may need specific imaging clues to perform the segmentation.

- Anatomical relationships between the neighboring structures are valuable information to assist the segmentation.

- Incorporating prior knowledge to the segmentation can considerably improve the performance of the segmentation algorithms.

- Due to the complexity of the medical images, a fully automatic segmentation algorithms that are robust to images under different conditions still need considerable work.
Acknowledgement

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“Methodologies to Analyze Organs from Complex Medical Images – Applications to Female Pelvic Cavity”, PTDC/EEA-CRO/103320/2008
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