Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Anatomically Based Computational Models of the Male and Female Pelvic Floor and Anal Canal

K. F. Noakes, I. P. Bissett, A. J. Pullan and L. K. Cheng

Abstract— **The understanding of the pelvic floor and anal canal, in the study of incontinence, has been limited by the inability to integrate both anatomy and physiology into a unified bioengineering model. However, this integration has been achieved in the study of other organs in the body, most notably the heart. In this study we construct three-dimensional anatomically realistic models of both the male and female pelvic floor and anal canal regions using similar techiniques to those used in cardiac modelling. Anatomical data from the Visible Human Project was used to provide the anatomical positioning of each model component within the region of interest. A C^1 continuous cubic Hermite finite element mesh was then created using an iterative linear fitting procedure (Root Mean Square (RMS) error of fit < 2 mm). With this mesh we seek to examine the roles of the various muscles in maintaining continence. Our ultimate aim is to provide a framework with which to examine the mechanics of normal function and stability in the pelvic floor, and the abnormalities associated with the defecation disorders fecal incontinence and obstructed defecation, thereby providing a tool to further the education of clinicians, patients, and students and enabling virtual planning of corrective surgery.**

I. INTRODUCTION

It has been estimated that the incidence of some form of fecal incontinence among the population of New Zealand is as high as 11%-15% [1] while in a recent French study it was found that over 20% of the population suffer from obstructed defecation [2]. Fecal incontinence occurs when the muscles in the pelvic floor lose their ability to restrict the release of rectal content from the anal canal, while obstructed defecation (or outlet constipation) is defined as an inability to adequately evacuate contents from the rectum [3].

There are four main muscle groups believed to be involved in maintaining continence in the human body: the internal anal sphincter, external anal sphincter, puborectalis and the levator ani muscle group. The internal anal sphincter is an involuntary smooth muscle which maintains continuous background tone and is responsible for maintaining all day continence. This muscle is a thickened distal extension of the inner circular muscle of the rectal wall [4] and responds to changing rectal pressures. The internal anal sphincter resides in the upper two thirds of the anal canal and is partially surrounded by the external anal sphincter, a powerful skeletal muscle under voluntary control. The external anal sphincter is classically divided into three sections (subcutaneous, superficialis and deep) lying adjacent to each other in series around the lower two-thirds of the anal canal [4]. The levator ani muscle group consists of three main striated muscles – pubococcygeus, iliococcygeous and puborectalis. In this study, as in the modern imaging and anatomic literature, we consider puborectalis to be a separate entity from levator ani. These muscles play active roles in pelvic organ support with the levator ani raising the pelvic floor and providing resistance to increased internal rectal pressure, and the puborectalis muscle (positioned in a sling-like fashion wrapping around the back of the rectum) forcing the anorectal junction in an anterior direction toward the pubis and providing extra assistance to the action of the sphincter muscles [5]. Malfunction of any of these main muscles of the pelvic floor can result in major defecation disorders such as fecal incontinence or obstructed defecation.

Incontinence in women (both urinary and fecal) can also arise through damage to the pelvic floor muscles as a consequence of a difficult vaginal birth [6]. A prolonged second stage of labour (the period when the baby moves down from the uterus, through the cervix and into the vaginal canal) is undesirable and is known to be one of the factors which causes damage to those muscles in the pelvic floor surrounding or in close proximity to the vaginal canal [7]. Muscles such as the rectal wall muscles, the two sphincter muscles and the puborectalis and levator ani muscles lie around or against the vagina and hence, are disturbed as the baby passes down from the uterus during labour.

The ability to accurately construct a geometric representation of the components of the pelvic floor, and their spatial relationship, is a critical component in obtaining an accurate non-invasive representation of the functional anatomy of the pelvic floor. To date, the geometry of pelvic floor components has been obtained through two-dimensional (2D) digitization or through semi-automated image segmentation programs which can exclude critical details and/or components. In this study three-dimensional anatomically-based computational models of both the male and female pelvic floor regions have been constructed from the Visible Human Project data [8]. These models provide a framework for future work to examine the functional behaviour of the pelvic floor in both a normal and diseased state and, in the case of the female model – may help provide an early diagnosis protocol for factors that could predispose the mother to elect delivery via cesarean section.

K. F. Noakes, L. K. Cheng and A. J. Pullan are with the Bioengineering Institute, The University of Auckland, New Zealand (email: kim.noakes@auckland.ac.nz)

I. P. Bissett is with the Department of Surgery, The University of Auckland

This work was financially suppoprted by a NZIMA (New Zealand Institute of Mathematics and its Applications) Masters Scholarship, RSNZ (Royal Society of New Zealand) Marsden Grant (UOA320), RSNZ James Cook Fellowship, and the National Institutes of Health (R01 DK64775).

1-4244-0033-3/06/$20.00 ©2006 IEEE.

II. METHODS & RESULTS

We have created geometric computational models of key components in both the male and female pelvic floor regions. To create the model, data points corresponding to the components of interest were digitized from images obtained using the Visible Human Project data sets as described below. A least squares fitting technique was used to minimize the model error on the finite and boundary elements. The components of interest in the male pelvic floor are: puborectalis (PR), levator ani (LA), rectum, internal and external anal sphincters (IAS and EAS respectively), pubis, coccyx, transverse perineae (TP), and the urethra/prostate and bulbospongiosus group (UPBS). In the female the components modelled were the PR, LA, rectum, IAS, EAS, obturator internus (OI), vagina, uterus, bladder, pubis, coccyx, TP, perineal body (PB) and the bulbospongiosus muscle.

A. Data Acquisition

Axial photographic images from the Visible Human Project [8] were used to acquire the initial geometric information necessary for the models. The Visible Human Project provides the highest resolution data set currently available, therefore, despite that fact that the images are of cadavers, we felt that it was best to create our initial models from these images. The boundaries of each of the components of interest within the pelvic floor (10 components in the male and 15 in the female) were manually traced on each image "slice", and independently reviewed by a specialist. The image shown in Fig. 1 is a slice from the Visible Woman data set at a level just below the bladder and cervix. Data points on each slice were combined to form a set of data points (a total of 7,605 data points for the male and 12,991 data points for the female) which provided surface information for each of the component in the pelvic floor as shown in Fig. 2(a) and Fig. 2(b).

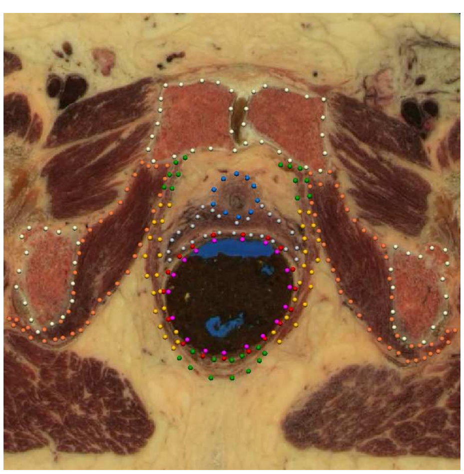
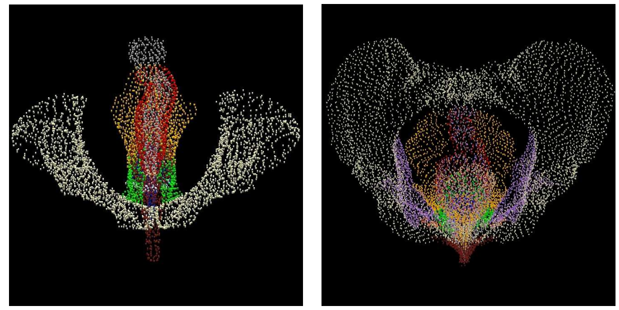


Fig. 1. Digitized visible woman slice outlining puborectalis (green), levator ani (yellow), rectum (red), lumen (pink), obturator internus (orange), vagina (silver), pubis bone (white) and the urethra (blue).



(a) (b)

Fig. 2. Traced slices are combined to give a "data cloud" of anatomical information. Fig. (a) shows the data points for the 10 digitized components from the Visible Man and (b) shows the 15 digitized Visible woman components. Note the extra anatomical features included in the Visible Woman. The PR muscle, levator ani muscle group and pubis bone can be easily identified in both models in green, gold and white respectively.

B. Texture Block Re-sectioning

In order to improve the accuracy of our manual digitization, the more anatomically representative Visible Woman data set is digitized in three dimensions (3D). Initially, the original axial images provided from the Visible Human Project were used to create as precise a data set as possible through careful 2D digitization, and the greater resolution of the Visible Woman images (pixel size 0.3 mm $\times$ 0.3 mm $\times$ 0.3 mm) in comparison to the Visible Man images (pixel size 0.3 mm $\times$ 0.3 mm $\times$ 1 mm) enabled the component boundaries to be more easily recognised. Once 2D digitization in the axial view had been completed, the image planes in the remaining dimensions were produced and made compatible for digitization.

A total of 444 axial images at 0.3 mm intervals from the Visible Woman data set, corresponding to the pelvic floor region, were grouped to form a large volume "texture" of images comprised of a total of 580 megapixels. As the resolution is the same in all three directions in the Visible Woman, it is possible to exactly interpolate between the pixels and resection the volume in both the coronal and sagittal views (see Fig. 3) to get new images of size 1516 pixels $\times$ 444 pixels (coronal) and 862 pixels $\times$ 444 pixels (sagittal).

Two views were used simultaneously to review the digitized points in 2D: one remained at all times in the axial view, while the second was used to view either the coronal or sagittal planes. Markers, placed at the borders of the axial plane, indicate the positioning of the alternative viewing plane to provide orientation to the user. As digitization was performed exclusively on the axial image, the resectioned views were used as positioning guides and enabled every traced data point in the axial plane to be reviewed and repositioned according to its placement on these alternative anatomical views (seen in Fig. 4).

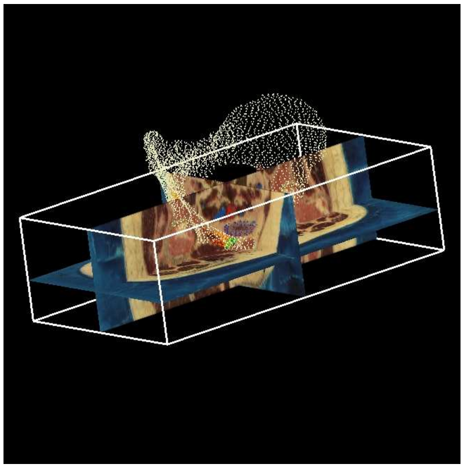
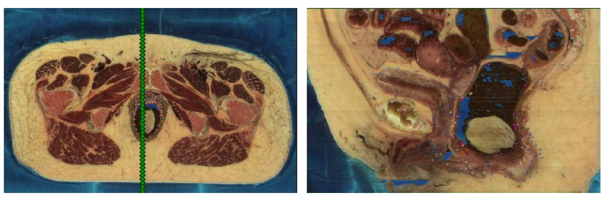


Fig. 3. An original Visible Woman axial image and two reconstructed coronal and sagittal viewing planes – created through interpolation of the volume texture (indicated by the surrounding wire frame).



(a) (b)

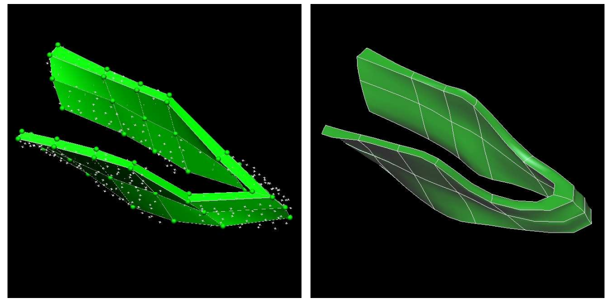
Fig. 4. Axial view used for digitizing the Visible Woman is seen in (a) while (b) shows the sagittal plane used to review the digitized points. The green bar in (a) indicates the position of the sagittal image in (b).

C. Mesh Creation

Following the 3D digitization process, the traced data sets were used to form finite element (FE) and boundary element (BE) models. Node points were selected from the two data sets and used to form 3D finite elements. An initial volume mesh was constructed for each model using FE interpolation with linear basis functions as seen in Fig. 5(a), and each traced data point was projected orthogonally onto the closest face of the mesh with the smallest distance between the two calculated using the Newton-Rhapson Method. An iterative FE procedure with 3D cubic Hermite basis functions [9] was used to provide smooth C^1 continuous surfaces for each pelvic floor component (shown in Fig. 5(b)). By iteratively fitting the mesh the Root Mean Square (RMS) error between the traced data points and its projected position on each element surface was minimized, and the model components take on an anatomically realistic appearance. The fitting method can be expressed mathematically as:

$$\text{min. } F(u) = \sum_{d=1}^{D} w_d \|\boldsymbol{u}(\xi_d) - \boldsymbol{u}_d\|^2 \quad (1)$$

where d is one data point from a total of D digitized data points, having a weighting w_d and position $\boldsymbol{u}_d$ and $\boldsymbol{u}(\xi_d)$ is the location of the orthogonal projection of that data point onto the corresponding surface of the generic model. In practice, all data point weightings are typically equal to 1, but they can be varied to express relative confidence in the accuracy of the digitized location.



(a) (b)

Fig. 5. Puborectalis muscle: Nodes are identified and combined to form linear finite elements (a). These are then fitted using an iterative non-linear fitting technique to provide a realistic representation of the component (b).

D. Visible Man Results

Geometric fitting has been completed for the Visible Man data set and the final model can be seen in Fig. 6. Results for each of the pelvic floor components in the Visible Man gave a RMS error less than 2 mm (see Table I).

TABLE I
RMS ERROR (MM) OF THE 10 FITTED PELVIC FLOOR COMPONENTS FROM THE VISIBLE MAN.

Component Name	*No. Data Points*	*No. Nodes*	*No. Elements*	*RMS Error*
PR	640	66	20	0.571
LA	918	59	20	0.939
Rectum	696	48	42	0.573
Lumen	565	60	54	0.395
IAS	207	42	18	0.892
EAS	708	54	24	1.019
Pubis	1168	96	84	1.266
Coccyx	219	38	42	0.527
TP	89	18	12	1.012
UPBS	567	42	36	0.717

III. DISCUSSION & FUTURE DEVELOPMENTS

The number of pelvic floor components, and the level of detail for each component, were considerably higher in the model based on the images from the Visible Woman data set. This was primarily due to two factors which caused the Visible Woman data to be seen as the superior data source over the Visible Man. In the first instance, the female data set is of a higher resolution because the image separation is reduced – each image is 0.3 mm apart from its neighbours compared with the 1 mm slice separation in the male. This means that components appear clearer in the female images which consequently improves the accuracy of digitisation and hence the female model. Secondly, the rectum and anal canal in the male data set appear to be squashed and do not lie

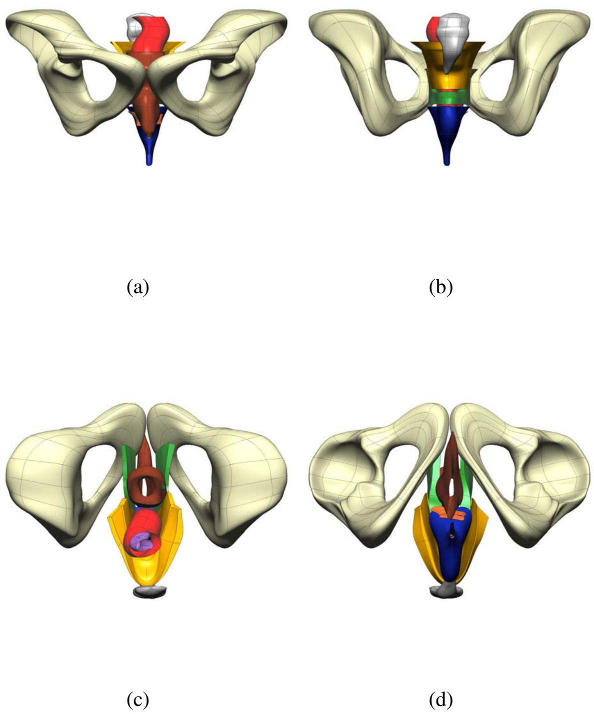


Fig. 6. Final fitted models of the Visible Man data set. Anterior view (a), posterior view (b), cephalad view (looking down) (c) and caudad view (looking up) (d) showing 9 of the 10 components – PR (green), LA (gold), EAS (blue), rectum (red), lumen (purple), TP (orange), pubis (white), coccyx (silver) and UPBS group (brown).

in the normal orientation that is expected in live subjects. This phenomenon is thought to have been caused by the post-mortem perineal pressure on the posterior surface of the cadaver before it was frozen and imaged, and does not allow an accurate representation of the pelvic floor region to be constructed.

The aim of this research is to have an accurate representative 3D model of both the male and female pelvic floor regions so that we can improve the understanding of a complicated area and understand how components within this region may interact. These models will provide a framework with which to examine the mechanics of normal function and the abnormalities associated with the defecation disorders fecal incontinence and obstructed defecation, thereby providing a tool to further the education of clinicians, patients, and students and enabling virtual planning of corrective surgery. Initially, we aim to determine the relative importance of various muscles in maintaining continence and pelvic floor stability. We also aim to produce patient specific models using MR images, and these initial FE models, based on the Visible Human Project data, will be used to help navigate through the lower quality MR image sets to build the new models.

IV. ACKNOWLEDGMENTS

The authors would like acknowledge the assistance of Professor Stuart Heap from Mercy Hospital and The University of Auckland in assisting with pelvic floor anatomy identification, and Jenny Kruger from The University of Auckland Sports Science Department for helpful discussions in the area of childbirth and its related complications.

REFERENCES

[1] A. K. Macmillan, A. E. H. Merrie, R. J. Marshall, and B. R. Parry, "The prevalence of fecal incontinence in community-dwelling adults: A systematic review of the literature.," *Dis Colon Rectum*, vol. 47, no. 8, pp. 1341–1349, 2004.

[2] L. Siproudhis, F. Pigot, P. Godeberge, H. Damon, D. Soudan, and M. A. Bigard, "Defecation disorders: a French population survey.," *Dis Colon Rectum*, vol. 49, no. 2, pp. 219–27, 2006.

[3] G. R. Locke, J. H. Pemberton, and S. F. Phillips, "Aga technical review on constipation.," *Gastroenterology*, vol. 119, no. 6, pp. 1766–1778, 2000.

[4] R. J. Last, ed., *Anatomy, Regional and Applied*. Churchill Livingstone - Medical Division of Longman Group Limited, 1984.

[5] R. T. Woodburne, ed., *Essentials of Human Anatomy*. Oxford University Press, 1983.

[6] C. MacArthur, D. E. Bick, and M. R. Keighley, "Faecal incontinence after childbirth.," *Br J Obstet Gynaecol*, vol. 104, no. 1, pp. 46–50, 1997.

[7] H. P. Dietz, "Levator function before and after childbirth.," *Australian and New Zealand Journal of Obstetrics and Gynaecology*, vol. 44, pp. 19–23, 2004.

[8] V. Spitzer, M. J. Ackerman, A. L. Scherzinger, and D. Whitlock, "The visible human male: A technical report," *J. Am. Med. Inform. Assoc.*, vol. 3, pp. 118–130, Mar. 1996.

[9] C. P. Bradley, A. J. Pullan, and P. J. Hunter, "Geometric modeling of the human torso using cubic Hermite elements," *Ann. Biomed. Eng.*, vol. 25, pp. 96–111, 1997.