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Subject specific finite elasticity simulations of the pelvic floor

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ABSTRACT

An anatomically realistic computational model of the pelvic floor and anal canal regions was used in this study to examine the mechanics of normal defecatory function within the female pelvic floor. This subject specific, MRI-based model enabled mechanical simulations to be performed and quantitatively assessed against experimental data retrieved from the same volunteer. The levator ani muscle group mesh was used as the domain over which the governing equations of finite elasticity were solved using the finite element method with a Mooney–Rivlin material law. Deformation of the levator ani was simulated during a 'bear down' maneuver in order to visualize the way this muscle group functions in an asymptomatic subject. A pressure of 4 kPa was imposed on the mesh and the computed mesh displacements were compared to those obtained from dynamic MR images with an average, experimentally consistent, downwards displacement of 27.2 mm being achieved. The RMS error for this movement was 0.7 mm equating to a percentage error of 2.6% in the supero-inferior direction and 13.7 mm or 74.5% in the antero-posterior direction.

1. Introduction

One in every 10 women will, at some point in their lives, suffer a form of pelvic floor dysfunction (PFD) so severe that it will require surgery, with one-third of these undergoing repeated surgical procedures (Olsen et al., 1997). PFD results from specific damage to, or atrophy of, the muscles, fascial structures and nerves of the pelvic floor. The spectrum of dysfunction is vast, and abnormalities of the pelvic floor can lead to defecation disorders such as fecal incontinence or obstructed defecation (Smith and Witherow, 2000). Fecal incontinence is a disorder that affects people of all ages. It is, however, more common in women and in older adults, but is not considered a normal part of the aging process. It remains unclear whether muscle damage or neuropathy is the primary mechanism for the development of PFD, but some authors believe that the PFD is largely caused by damage to the connective tissues (ligaments and fascia) and muscles of the pelvic floor. The combined action of ligaments, fascia and muscles anchors the pelvic organs, and the urethra, vagina and anal canal. The normal function of the pelvic organs is thus dependent on the integrity of the pelvic floor (Petros, 2004).

Normal defecatory control requires the complex integration of neurological pathways and four main muscle groups in the pelvic floor and anal canal: the internal anal sphincter (IAS), external anal sphincter (EAS), puborectalis (PR) and the levator ani (LA) muscle group. It also requires the ability to adequately determine anorectal contents, and the ability to access the necessary facilities to evacuate the rectum. In particular, the LA is important in controlling defaecation as it acts together with the striated muscle of the anterior abdominal wall, to generate intra-abdominal pressure (IAP). Any increase in IAP (e.g., caused by sneezing or coughing) is applied equally to all sides of the pelvic and abdominal walls. If the LA is pathologically weakened or temporarily inactivated, the pressure on one side of a pelvic organ may become greater than that on the other, allowing the organ to descend (genital prolapse). If this movement carries the organ outside the pelvic cavity, pressure acting on the content of that organ will be directed unequally and in the case of the bladder or rectum could cause urinary or faecal incontinence (Janda et al., 2003). The shape of the LA and regional thickening during different levels of physiological loading can provide an indication of PFD (Lee et al., 2004).

In the past, the poor selection of patients, insufficient baseline investigations and poorly audited surgical techniques, have led to unacceptable levels of surgical failure. In many cases, patients and their symptoms were not adequately assessed, which may have led to a delay in diagnosis, with prolonged morbidity and unnecessary or inappropriate surgical procedures (Smith and Witherow, 2000). The ability to accurately simulate LA muscle function will enable clinicians to better understand the

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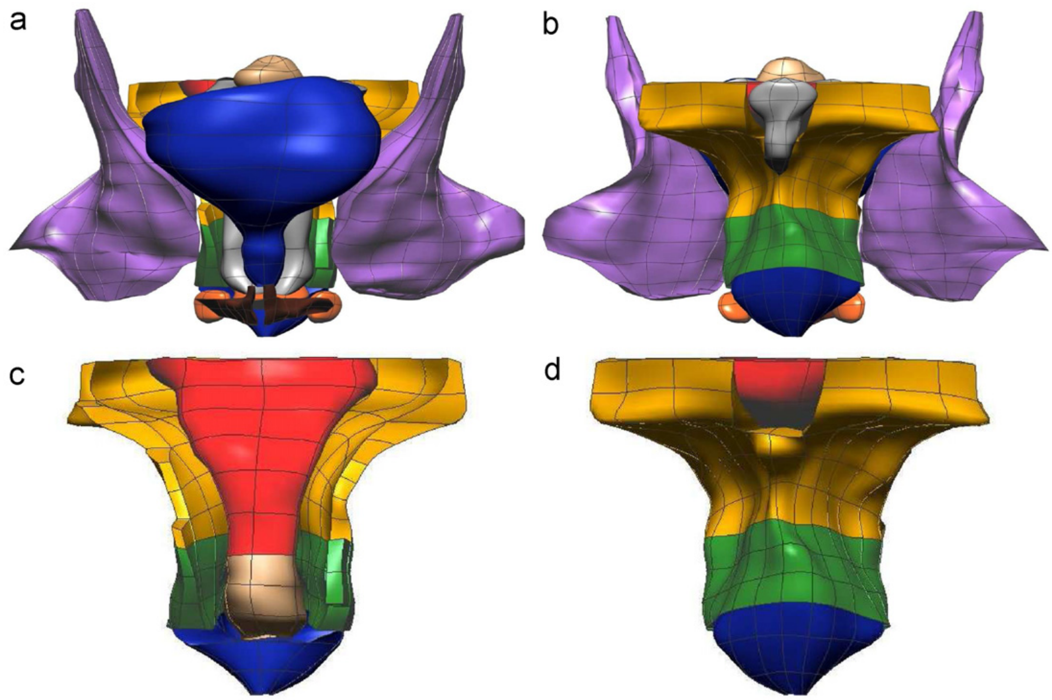

Fig. 1. The final fitted models from the MRI data set. Shown are (a) anterior and (b) posterior views showing 12 of the 13 components—levator ani (LA) (gold), puborectalis (PR) (green), external anal sphincter (EAS) (blue), internal anal sphincter (IAS) (beige), rectum (red), transverse perineae (orange), perineal body (orange), coccyx (silver), uterus (beige), vagina (silver), obturator internu (OI) (purple) and bulbospongiosus (brown). Also shown are enlarged views of the (c) anterior and (d) posterior of the LA, PR, EAS, IAS and rectum. For clarity the lumen has not been shown in these views.

anatomical and physiological defects which may be affecting normal defecatory function in patients and thereby select the most appropriate treatment for each individual.

Few of the currently available geometric pelvic floor models are suitable for finite element analysis. One of the most advanced numerical models to date is the d'Aulignac et al. (2005) model which uses shell finite elements to reconstruct the LA muscle in three dimensions. Muscle fiber direction and tissue incompressibility were included in the model to help simulate the muscle under pressure and with active contraction. However, the geometry for the d'Aulignac et al. (2005) model was constructed using data from a 72 year old female cadaver and therefore may not be representative of live subjects.

The purpose of this study is to present simulation results of LA muscle function using the finite element method on computational meshes based on live subject data.

2. Pelvic floor model

An anatomically realistic female pelvic floor model, based on live subject MRI data (previously described in detail in Noakes et al., 2008), was used as the basis of the simulation environment. The model was constructed from 120 cross-sectional T2 weighted MRI images, with a base resolution of 384×384 pixels with a 1 mm slice separation. The subject was a healthy, nulliparous, 32 year old female volunteer. Ethical approval and informed consent were obtained for the MRI data to be used in this study.

The boundaries of each of the pelvic structures in the model were delineated via manual data point placement on each MR image. A total of 19,678 data points were traced around 13 components of interest including the rectum, vagina, uterus and bladder (including urethra), the PR muscle, the LA muscle group, the IAS and EAS, respectively, the transverse perineae (TP) muscles, obturator internu (OI) muscles, the bulbospongiosus muscle, the coccyx bone and the perineal body (PB). Initial trilinear finite elements were constructed around each data cloud. A least-squares iterative fitting technique was then used to minimize the distances between each data point and its orthogonal position on the initial mesh (Bradley et al., 1997; Cheng et al., 2005). The final fitted surface and volume meshes (shown in Fig. 1) were interpolated using tricubic Hermite basis functions to give a realistic appearance to the anatomical geometries and had an average RMS error of less than 0.75 mm between the data points and final fitted mesh surfaces.

3. Mechanical modelling: valsalva pressure on the LA muscle

The LA muscle was represented using 160 nodes and 58 tricubic Hermite elements. The finite elasticity deformation simulations were performed using the CMISS[1] software package. For simulation purposes the LA muscle group was created with the local coordinate system (ξ_1, ξ_2, ξ_3) defined as follows: ξ_1 running (subject's) right to left around the muscle, ξ_2 running in a superior/inferior direction and ξ_3 running in a medio-lateral direction.

Pressure was applied orthogonally to the anterior surface of each of the muscle elements to simulate the deformation experienced by the LA muscle during a 'bearing down' abdominal squeeze maneuver, performed by increasing IAP while relaxing the pelvic floor muscles, as is carried out in the process of evacuation of the bowel or during the delivery of a baby (Parente et al., 2007).

Understanding and predicting the deformation of a material under varying distributions of applied stresses and strains is fundamental to understanding its function. Biological materials

[1] http://www.cmiss.org/