Quantity and distribution of levator ani stretch during simulated vaginal childbirth

Lennox Hoyte, MD; Margot S. Damaser, PhD; Simon K. Warfield, PhD; Giridhar Chukkapalli, PhD; Amitava Majumdar, PhD; Dong Ju Choi, PhD; Abhishek Trivedi, PhD; Petr Krysl, PhD

OBJECTIVE: The objective of the study was to develop a model of the female pelvic floor to study levator stretch during simulated childbirth.

STUDY DESIGN: Magnetic resonance data from an asymptomatic nulligravida were segmented into pelvic muscles and bones to create a simulation model. Stiffness estimates of lateral and anteroposterior levator attachments were varied to estimate the impact on levator stretch. A 9 cm sphere was passed through the pelvis, along the path of the vagina, simulating childbirth. Levator response was interpreted at 4 positions of the sphere, simulating fetal head descent. The levator was color mapped to display the stretch experienced.

RESULTS: A maximum stretch ratio of 3.5 to 1 was seen in the posteriomedial puborectalis. Maximum stretch increased with increasing stiffness of lateral levator attachments.

CONCLUSION: Although preliminary, this work may help explain epidemiologic data regarding the pelvic floor impact of a first delivery. The models and simulation technique need refinement, but they may help study the effect of labor parameters on the pelvic floor.

Key words: childbirth simulation, pelvic magnetic resonance imaging, levator ani

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Female pelvic floor dysfunction (PFD) includes urinary incontinence and pelvic organ prolapse (POP). Urinary incontinence affects 17-55% of older women and 12-42% of younger women,[1] at a direct annual US cost of $12 billion.[2] Pelvic organ prolapse affects up to 50% of women over 50 years old.[3] It is the most common indication for hysterectomy in the United States,[4] and the annual direct cost of POP related surgery was $1 billion in 1997.[5] Significant risk factors for pelvic floor dysfunction are believed to include childbirth, and epidemiologic data suggest that the first delivery is the most significant contributor to the development of urinary incontinence.[6]

Study data have suggested that childbirth-related injury to the nerves and muscles of the pelvic floor may lead to the development of urinary incontinence.[7] In addition, detailed pelvic magnetic resonance imaging (MRI) studies have shown that visible puborectalis muscle damage occurs singularly in vaginally parous women and is considerably more prevalent in parous women with stress urinary incontinence, compared with those without stress urinary incontinence.[8] Other imaging studies have suggested that bony pelvic shape may also be a risk factor for the development of childbirth-related prolapse and that the more obstetrically suitable pelvis may be associated with increased rates of pelvic organ prolapse.[9,10]

To help elucidate which childbirth parameters may influence these PFD risk factors, Lien et al[11] performed computer simulations of vaginal childbirth and demonstrated that the pubovisceral portion of levator ani is subject to stretch ratios of greater than 3:1 during the delivery of the fetal head.

Our group sought to better understand the distribution of the actual stretch within the levator muscles, with a view to evaluating the impact of childbirth parameters (eg, maternal bony pelvic shape, and levator ani muscle bulk) on the stretch distribution during childbirth.

Therefore, the objective of this study was to develop an MRI-based 3-dimensional simulation model of the female pelvic floor and use the model to study the quantity and pattern of levator ani stretch during vaginal childbirth.

MATERIALS AND METHODS

The subject is a 21 year old, asymptomatic nulligravida who presented for pelvic magnetic resonance evaluation to evaluate for a uterus didelphys. She was considered to be of normal height and not obese. The imaging protocol was a high-resolution axial MRI scan, taken in the supine position, ranging from the ischial tuberosities inferiorly, up to the upper aspect of the acetabulae.

The imaging protocol was as follows: T2-weighted axial source images were obtained using a 1.5T magnet (General

From the Department of Obstetrics and Gynecology, Brigham and Women's Hospital (Dr Hoyte) and Harvard Medical School (Drs Hoyte and Warfield), Boston, MA; the Cleveland Clinic Foundation, Cleveland, OH (Dr Damaser); and the University of California–San Diego, San Diego, CA (Drs Chukkapalli, Majumdar, Choi, Trivedi, and Krysl).

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Dr Hoyte is now with the Department of Obstetrics and Gynecology, University of South Florida College of Medicine, Tampa, FL.

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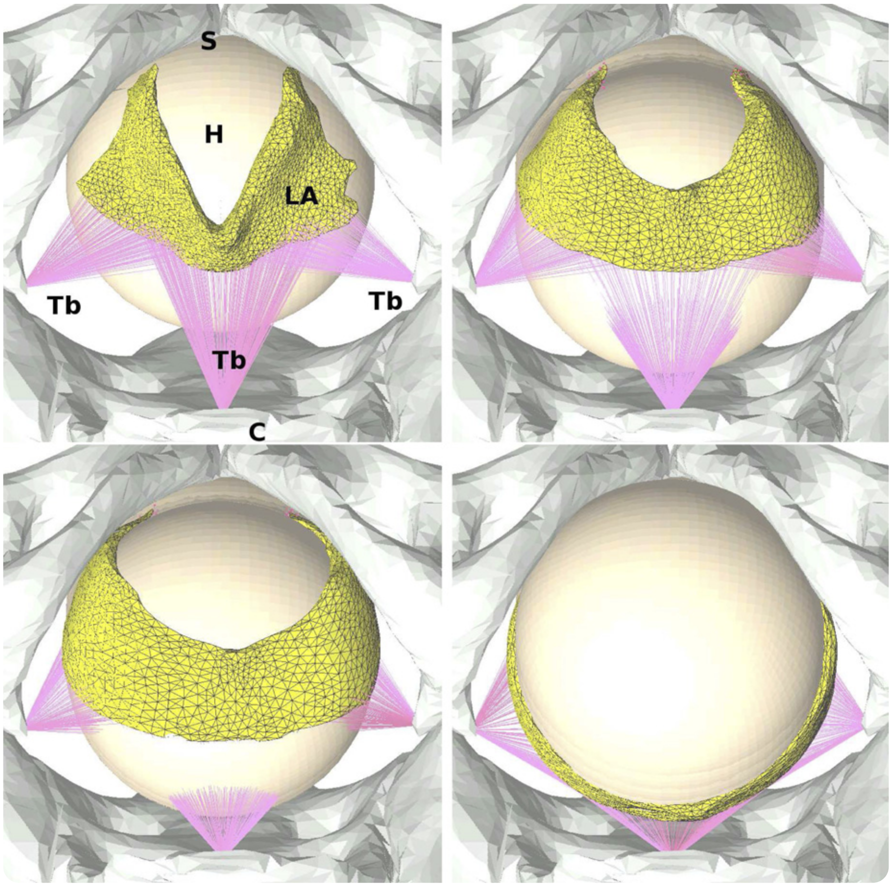
FIGURE 1
Axial view of the levator childbirth model



Axial view of the levator childbirth model showing the fetal head (H) interacting with the levator ani muscle (LA) during the simulation of childbirth. Left to right, top to bottom are the labor stages: 0 (resting), 1 (head at ischial spines), 2 (head past ischial spines), and 3 (crowning). Also shown are the suspension ties, which tether the levator posteriorly to the coccyx and the ischial spines. The anterior and lateral ties are not shown. The pelvic bones do not participate in the simulation and are considered rigid and immovable (in other words, the margins of the pelvic floor are stationary during the simulation). The bones are displayed here only as an orientation aid. *H*, head; *LA*, levator ani muscle; *C*, coccyx; *S*, symphysis; *Tb*, ties of anterior and posterior levator to symphysis and coccyx respectively.

Hoyte. Quantity and distribution of levator ani stretch during simulated vaginal childbirth. Am J Obstet Gynecol 2008.

Electric Medical Systems, Milwaukee, WI) and a torso phased array coil wrapped around the pelvis. The following imaging parameters were used: repetition time 4200 milliseconds, time to echo 108 milliseconds, 128 phase encodes, 24 cm field of view, and 3 mm slice thickness, no gap. Pixel dimensions were 0.781 × 0.781 mm. Institutional review board approval was obtained for review of the chart and images.

Image data were transferred to a Windows-based personal computer with advanced graphics capability. The 3-dimensional Slicer software (www.slicer.org)[12] was used to display and manually segment the gray-scale images into anatomically significant organs, such as the bladder, urethra, vagina, levator ani, obturator internus, bony pelvis, symphysis, and coccyx, in a manner similar to our previous work.[13]

Specialized finite element modeling and analysis tools[14-16,18] were then applied to the segmented structures to create an appropriate computer model of the bony pelvis, obturator internus, and levator ani muscles for simulation. These tools were used for decimating and smoothing the 3-dimensional models,[14] simplifying the topology of the 3-dimensional models to facilitate finite element analysis,[15] and for generating structural mesh models of the organs to enable the actual simulation.[16]

The mathematical deformation model was discretized with the element-free Galerkin method[17] and linear elastic geometrically nonlinear springs to represent attachments of the modeled muscles to other anatomical structures and the resulting ordinary differential equations were integrated with the centered difference method. Coarse and fine versions of the models were considered during the simulation to assess the discretization error.

No displacement boundary conditions were applied to the levator ani. For the purposes of simulation, the levator ani was assumed to attach anteriorly to the pubic bones, bilaterally to the arcus tendinous levator ani, and posteriorly to the coccyx. Ad hoc mechanical attachments via uniaxial ties was used.

The rationale for using attachments instead of the representation of the actual anatomical layers of the pelvic floor is 2-fold: the mechanical properties of this complex anatomical structure are known very poorly if at all, and the knowledge of the stretches in this part of the anatomy was not required as output of the simulation. The anterior and posterior attachments were modeled separately from the lateral attachments to independently quantify the effect of the uncertainty of the mechanical properties of each group of attachments.

There were no available model data for the living female pelvic floor structures, so plausible stiffness estimates based on the cross-section of the tissue and generally accepted range for connective tissue stiffness[18] were used for the anterior/posterior and the lateral attachments. To assess the effect of the estimated stiffness, the stiffness factor of each type of attachment (ie, anterior/posterior or lateral) was varied during the simulation to quantify the effect of varying stiffness on the amount and location of levator ani stretch.

For the purposes of simplicity in this initial model, the reconstructed levator muscle was assumed to be equally stretchable in all directions (ie, isotropic). The modified StVénant-Kirchhoff large-strain hyperelastic potential served as the model stress- strain response.

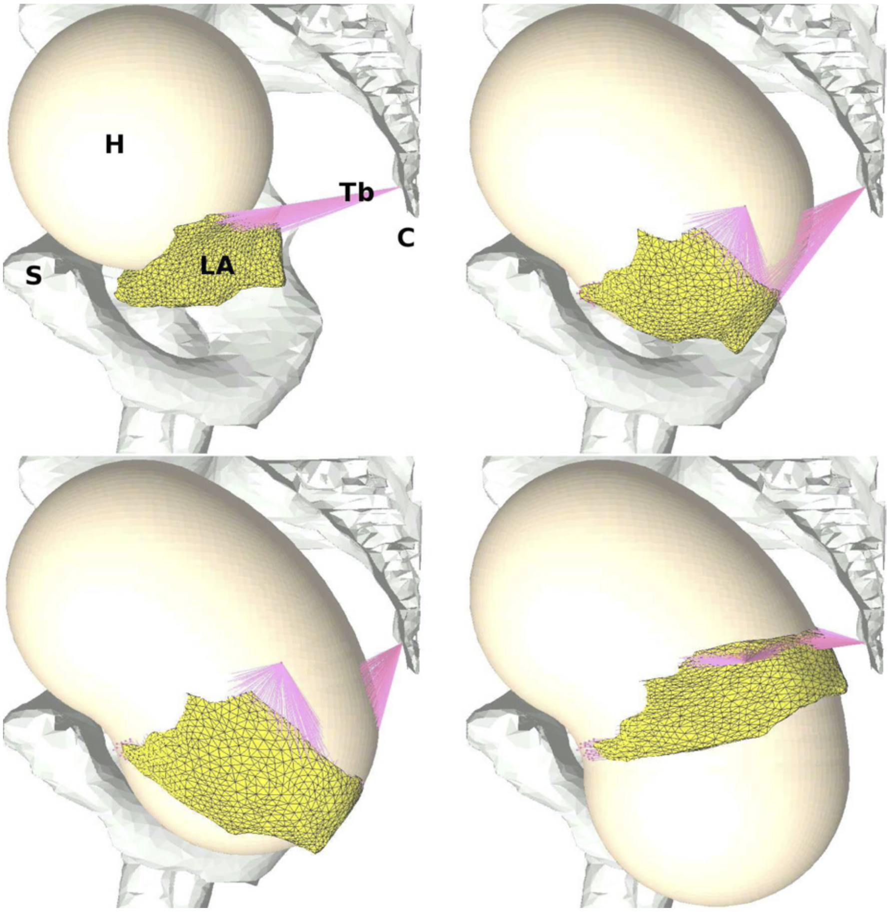
The parameters, the uniaxial Young's modulus and the Poisson's ratio, were derived by adopting a representative value of 66 kPa for the shear modulus of human muscle from the literature,[17] which then yields the Young's modulus of 0.2 MPa from the almost incompressibility of the fluid-saturated muscle. Finally, by setting the bulk modulus of muscle equal to the bulk modulus of water, the Poisson's ratio was derived.

To model vaginal childbirth, a sphere of 9 cm diameter, approximating the size of a molded fetal head, was passed through the pelvis, along the path of the vagina, to simulate passage of a term fetal head during vaginal childbirth.

The response of the pelvic floor was interpreted at 4 different positions of the fetal head: above ischial spines, in the proximal true pelvis, in the distal true pelvis, and exiting the levator hiatus. The simulation model was color coded to show the amount of stretch experienced by each point of the levator ani muscle at each point of the simulation. The resulting simulation images were rendered on a computer screen for visual and quantitative evaluation at each simulation point.

Whereas the model may be considered validated for simulations of purely mechanical action of generic human muscles,[17] it must be considered not validated for this particular application. The primary difficulty of validating the model is the paucity (or complete absence) of experimental data, especially of the changes in mechanical properties of the pelvic floor muscles because of complex biochemical changes immediately before and during delivery.

FIGURE 2
Lateral view of the levator childbirth model



Lateral view of the levator childbirth model showing the fetal head (*H*) interacting with the levator ani muscle (*LA*) during the simulation of childbirth. Left to right, top to bottom are the labor stages: 0 (resting), 1 (head at ischial spines), 2 (head past ischial spines), and 3 (crowning). In the simulation, the fetal head is advanced, leaving copies of itself behind to simulate the rest of the fetal body. Also shown are the suspension ties, which tether the levator posteriorly to the coccyx and the ischial spines. The anterior and lateral ties are not shown. The pelvic bones are considered fixed and do not participate in the simulation. The bones are displayed only as an orientation aid. *H*, head; *LA*, levator ani muscle; *C*, coccyx; *S*, symphysis; *Tb*, ties of group (b).

Hoyte. Quantity and distribution of levator ani stretch during simulated vaginal childbirth. Am J Obstet Gynecol 2008.

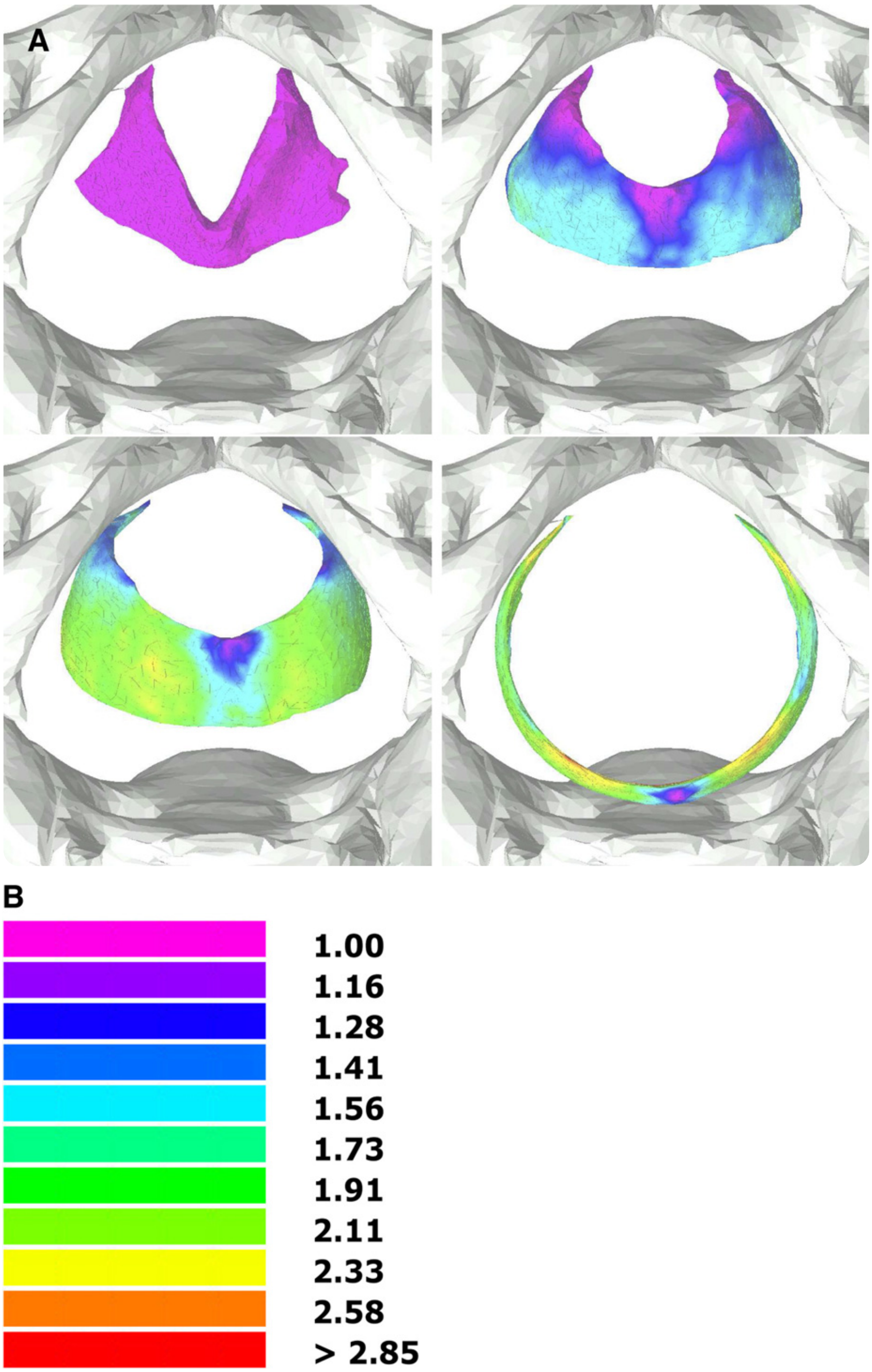
RESULTS

The simulations are shown in Figures 1-4. In Figure 1, an axial view of the resting levator is shown, together with the sequential changes observed as the simulated fetal head reaches and passes the ischial spines, followed by crowning of the head. Figure 2 shows a lateral view of the same progression. These figures demonstrate that the descending fetal head at first distends the iliococcygeus portion of levator ani and then widens and lengthens the levator hiatus as the head exits.

Figures 3 and 4 show color-coded versions of the distending levators at each stage of head descent (Figure 3, **A**, axial view; Figure 3, **B**, color legend; Figure 4, coronal view). In Figure 4, a maximum stretch ratio of about 3.5 to 1 was seen in the inner posteriomedial portion of the puborectalis part of the levator ani during simulated vaginal childbirth (Figure 4, bottom images).

When the stiffness of the lateral attachments of levator ani (iliococcygeus to arcus tendineous levator ani attachments) was decreased in the simulation, decreases in the maximal levator stretch resulted. A 5-fold decrease in the lateral attachment stiffness resulted in a decrease in the maximum stretch ratio from 3.5 to 1 down to about 3.0 to 1, or a

FIGURE 3
Axial view showing areas of stretch



A, Axial view showing the color-coded levator to demonstrate the stretch at the different levels of fetal head descent. Left to right, top to bottom are: head above ischial spines, head at ischial spines, head past ischial spines, and crowning. Maximal stretch of about 2.1 to 2.6:1 is seen on the outer posteromedial portions of the puborectalis (*green* and *yellow/orange* regions). The pelvic bones are considered fixed and do not participate in the simulation. The bones are displayed only as an orientation aid. The pelvic structures were defined in Figures 1 and 2. **B,** Color map definitions. The colors and numeric are shown. *Violet* indicates a stretch ratio of 1:1, and *red* indicates a stretch ratio of greater than 2.85 to 1 Intermediate stretch ratios are as shown in the figure.

Hoyte. Quantity and distribution of levator ani stretch during simulated vaginal childbirth. Am J Obstet Gynecol 2008.

14% decrease. Changes in the stiffness of the antero/posterior attachments had no impact on the maximum stretch ratio seen on the levator ani.

Comment

The model demonstrates that during simulated childbirth, maximal levator ani stretch occurred in the anteroinferior aspect of the levator ani muscles, specifically, the posteriomedial aspect of the puborectalis. The puborectalis was identified as the maximally stretched portion of levator ani in prior simulations by Lien et al,[11] but our work specifically localizes the maximum stretch to the posteriomedial portion of the puborectalis. Additionally, the present work suggests that increasing stiffness of the lateral attachments of the levator ani to the pelvic sidewall causes increased stretch on the levator ani muscles.

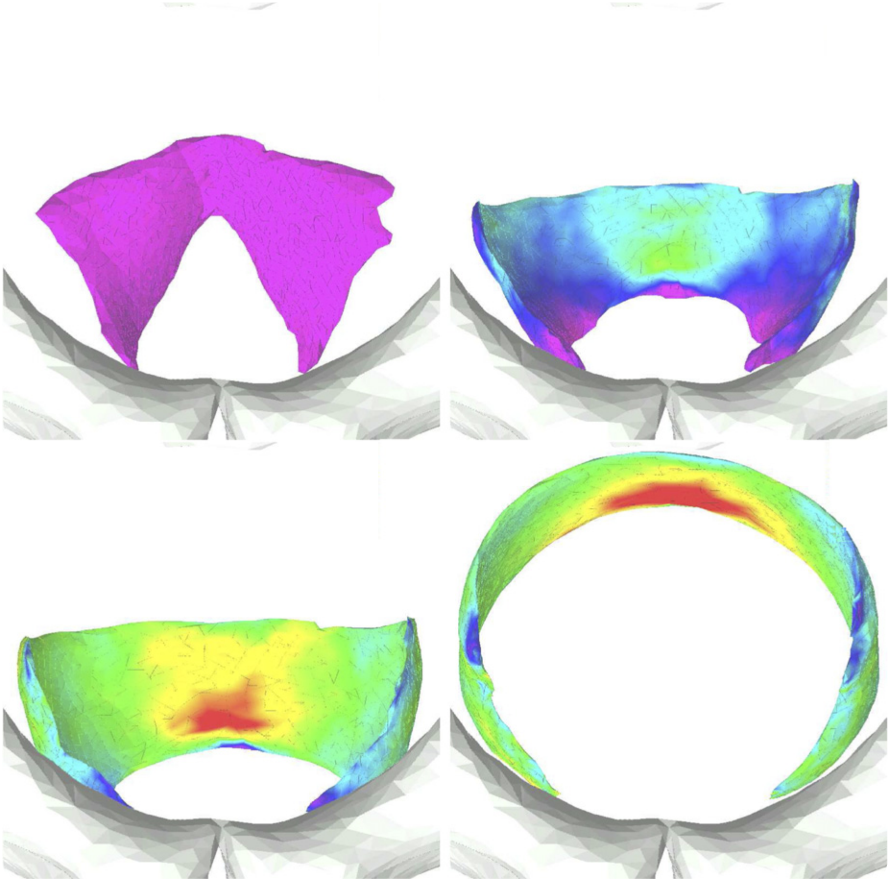
If the nulliparous levator is assumed to have stiffer attachments to the pelvic sidewall when compared with the levator after 1 or more vaginal deliveries, this finding would suggest that, for a given fetal head geometry and pelvis, the nulliparous levator may be subject to higher stretch ratios during childbirth when compared with the same levator after 1 or more vaginal deliveries.

This makes an intriguing hypothesis, which is supported by the epidemiological evidence that suggests that the initial vaginal delivery may confer the highest risk for the later development of urinary incontinence,[6] which is believed to be associated with hypermobility of the bladder neck.

The present simulation model is a preliminary work, which is limited by a lack of pregnancy specific models for the muscles and attachments of the pelvic floor as well as the assumption of equal multidirectional distensibility of the levator ani, which is known to have varying fiber orientations, and thus should have varying directional stretch response.

In addition, contributions because of fetal head molding and ischiorectal fat have not been considered in the initial simulations. However, the models produce plausible answers: based on a 2 centimeter genital hiatus at rest and a 11 cm genital hiatus at maximum distention by

FIGURE 4
Coronal view showing areas of stretch



Coronal view showing the color-coded levator to demonstrate the stretch at the different stages of labor. Left to right, top to bottom are: head above ischial spines, head at ischial spines, head past ischial spines, and crowning. Maximal stretch of 2.8 to 3.5:1 is seen in the posteromedial inner portions of the puborectalis (*orange/red* regions). The pelvic bones are considered fixed and do not participate in the simulation. The bones are displayed only as an orientation aid. The pelvic structures were defined in Figures 1 and 2. Color map definitions are given in Figure 3, **B**.

Hoyte. Quantity and distribution of levator ani stretch during simulated vaginal childbirth. Am J Obstet Gynecol 2008.

the fetal head, a puborectalis stretch factor of about 3:1 is to be expected with the passage of a 9 cm fetal head during labor.

Despite its limitations, the present technique permits further exploration of the relationships between the varying maternal/fetal labor parameters (eg, levator ani muscle characteristics, bony pelvic shape, and fetal head geometry) and the muscle stretch in labor.

It is important to note that the present modeling technique allows for the inclusion of updated model parameters (eg, muscle/attachment stiffness, tensile strength, and muscle fiber direction) because such parameters become available in the future. Perhaps more sophisticated versions of these models will help to pinpoint the specific, modifiable aspects of childbirth, which may hold the key to preventing childbirth-related pelvic floor injury in the future. ■

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