A Geometric Capacity–Demand Analysis of Maternal Levator Muscle Stretch Required for Vaginal Delivery

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Because levator ani (LA) muscle injuries occur in approximately 13% of all vaginal births, insights are needed to better prevent them. In Part I of this paper, we conducted an analysis of the bony and soft tissue factors contributing to the geometric “capacity” of the maternal pelvis and pelvic floor to deliver a fetal head without incurring stretch injury of the maternal soft tissue. In Part II, we quantified the range in demand, represented by the variation in fetal head size and shape, placed on the maternal pelvic floor. In Part III, we analyzed the capacity-to-demand geometric ratio, g , in order to determine whether a mother can deliver a head of given size without stretch injury. The results of a Part I sensitivity analysis showed that initial soft tissue loop length (SL) had the greatest effect on maternal capacity, followed by the length of the soft tissue loop above the inferior pubic rami at ultimate crowning, then subpubic arch angle (SPAA) and head size, and finally the levator origin separation distance. We found the more caudal origin of the puborectal portion of the levator muscle helps to protect it from the stretch injuries commonly observed in the pubovisceral portion. Part II fetal head molding index (MI) and fetal head size revealed fetal head circumference values ranging from 253 to 351 mm, which would increase up to 11 mm upon face presentation. The Part III capacity-demand analysis of g revealed that, based on geometry alone, the 10th percentile maternal capacity predicted injury for all head sizes, the 25th percentile maternal capacity could deliver half of all head sizes, while the 50th percentile maternal capacity could deliver a head of any size without injury. If ultrasound imaging could be operationalized to make measurements of ratio g , it might be used to usefully inform women on their level of risk for levator injury during vaginal birth. [DOI: 10.1115/1.4032424]

Introduction

The soft tissues surrounding the birth canal undergo remarkable elongation to allow a fetal head to emerge from the pelvis [1–3]. Unfortunately, the elongation can be such that approximately 13% of women delivering vaginally for the first time sustain stretch-related injuries of their LA muscles. These muscles partially surround the birth canal [4] and form the key soft tissue structures that must be dilated for delivery to occur. Using magnetic resonance imaging, researchers have identified the injuries as partial or complete damage of the left and/or right side pubovisceral muscle (PVM) portion of the LA [5]. These injuries are presently not treated surgically because the risks of repairing such deep structures outweigh any benefit that might derive. These injuries are found much more often in women with pelvic floor dysfunction, including pelvic organ prolapse. For example, the relative risk of prolapse compared to nulliparous women is 4 in women who have given birth to one child, and 8 in women who have given birth to two children [6]. Indeed, approximately 11% of all U.S. women undergo surgery later in life for pelvic organ prolapse, or urinary and fecal incontinence, with the leading risk factor for developing these conditions being vaginal birth (for review, see Ref. [7]). At present, it is not possible to predict which women will be injured during a vaginal birth. Furthermore, we do not know which prelabor maternal and fetal parameters might help predict injury. The goal of this paper is to provide the conceptual and mathematical framework to consider these questions and to report the results of our first analyses.

The factor of safety for a structure like a bridge is defined as the ratio of the capacity of the structure to resist, without failure, the loads applied divided by the maximum load, or demand, that it will be called upon to resist in service. Using this capacity-demand concept, one can define the geometric capacity-demand ratio, g , for vaginal birth as the ratio of maternal geometric capacity to pass a fetal head through the birth canal divided by the demand, which is represented by the size of the fetal head. More precisely, the maternal capacity can be defined as the largest internal circumference to which the soft tissues defining the narrowest part of the maternal birth canal can stretch without failure. The fetal demand is the maximum circumference of the fetal head presented to the narrowest part of the birth canal after molding of the fetal head; molding is the amount of fetal head compression needed to pass through the birth canal. If we disregard time-dependent effects for the moment, then when g is greater than unity, no levator injury will result. When g is much less than unity, levator injury will almost certainly result because the fetal head is too large to pass through the birth canal without stretching the maternal soft tissues beyond their ability to lengthen without rupture. But when g is just less than 1, there is uncertainty about whether injury will result. A goal of this paper is to determine the range of possible values for g based on the known variance in maternal and fetal geometries. In clinical practice, knowledge of the value of g might help the expectant mother better evaluate her different delivery options.

In terms of anatomy, when the fetal head passes through the birth canal, it is bounded by the front of the bony pelvis, comprised of the pubic symphysis with pubic rami on either side, and partly by the “U”-shaped soft tissue forming a loop laterally and posteriorly. As the second stage of labor progresses and the baby descends through the birth canal along the curve of Carus, the fetal head comes into contact with the more inferior regions of

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Fig. 1 Schematic illustration of the LA muscles. The subcomponents of the PVM (PPM; PAM, and PVaM) are shown. Left: schematic view of the LA muscles from below after the vulvar structures and PM have been removed showing the arcus tendineus levator ani (ATLA); external anal sphincter (EAS); PAM; PB uniting the two ends of the PPM; ICM; PRM. Right: the LA muscle seen from above looking over the sacral promontory (SAC) showing the PVaM. The urethra, vagina, and rectum have been transected just above the pelvic floor. (The internal obturator muscles have been removed to clarify levator muscle origins.) Recently, it has become clear that the origin of the PRM lies more caudal than is suggested in the illustration at left [8]. Copyright © DeLancey 2003 [9].

the pubic rami and different regions of soft tissue become progressively engaged by the fetal head. There has not been a detailed analysis of which soft tissues comprise those different regions of the U-shape because there has not been a precise anatomic description of the orientation of those soft tissues until recently [8].

In the case of the soft tissue loop, the LA muscles comprise the majority of the U-shaped soft tissue loop which surrounds the central opening, called the levator hiatus, through which the baby must pass. The soft tissue is comprised of several subdivisions; the pubovisceral (also known as the pubococcygeal), the puborectal, and the iliococcygeal portions (ICM) (Fig. 1). The PVM itself also has three components; the pubovaginal (PVaM), puboperineal (PPM), and puboanal (PAM) portions. These latter parts are simply aspects of the PVM rather than distinct muscles and will be considered here to form a single muscle. The upper arms of the U attach to the pubic rami on either side of the pubic symphysis. In the most important, distal, region of the U-shaped loop, the tissues which will undergo the greatest stretch are the PVM and the puborectal muscles (PRM) [1]. The PVM inserts distally onto the perineal body (PB) and lateral margins of the anal sphincter (AS). The PVM and PRM together form the narrowest part of the birth canal. It will be shown to be functionally important that the PVM originates on either side of the posterior aspect of the pubic symphysis while the PRM originates more caudally [8]. The reason this is functionally important is because when muscle injury occurs, it is the PVM on one or both sides that is injured, and not the PRM [5]; this, despite the fact that they both arise from the posterior aspect of the bone near the pubic symphysis and both encircle the levator hiatus through which birth occurs. There is presently no biomechanical explanation for this difference in the propensity for stretch injury and that is a secondary goal of this paper.

In Part I of this paper, we conduct a geometric analysis of the contributions of variations in the bony and soft tissue factors to the geometric capacity of the maternal pelvic floor to accommodate fetal head delivery without incurring maternal levator muscle stretch injury. We also conduct a sensitivity analysis of the maternal factors that contribute to the 50th percentile maternal pelvis capacity to deliver a fetal head of given size. The factors we considered include the SPAA, PVM and PRM origin placement,

initial SLs, and the effect of the downward rotation of the PVM and PRM around the pubic symphysis. In Part II, we quantify the range in demand represented by the variation in geometric size of the fetal head and variation in fetal head molding. As to the main goal of this paper, Part III, we use the results from Parts I and II to analyze the interaction between maternal capacity and fetal demand by calculating the values for g to understand whether a mother can deliver a head of given size without stretch injury. In the Discussion, we will consider the possibility of using prelabor ultrasound imaging to measure both maternal capacity and fetal demand in order to establish g for that individual.

Methods

Part I: Quantification of Factors Contributing to the Maternal Capacity for the 50th Percentile Woman. We hypothesized that anatomical differences between the PVM and PRM muscles help to explain why the PVM is injured but the PRM is not. It is known that in the standing posture, the PVM fibers angle downward from their origin high on the inside of the pelvis in a posterior direction [8]. By contrast, the PRM fibers angle upward from their origin low on the pelvis [8]. The two loops overlap one another laterally, with the PRM passing outside the PVM (Fig. 1). As labor progresses, the posterior PRM tissue is engaged first, followed by the anterolateral portion of the PVM [10]. Then, as the head is forced downward along the Curve of Carus, we assume that both loops are pushed downward, rotating about their origins, which lie on a mediolateral axis, much as a bucket handle about its hinges. Unlike bucket handles, however, they are stretched significantly as they rotate downward to reach the “ultimate crowning” configuration (Fig. 2). The lower margin of the pelvic bone forms an inverted valley, the SPAA, which is deeper as the fetal head moves downward, causing the head to ride along the bony ridges on either side, thereby bridging the inverted valley. The larger the SPAA, the further apart lie the ridge lines (Fig. 3). The origins of the PRM and PVM lie on the sides of the valley. As the head rides along the ridges approximately 90% of the PVM soft tissue loop actually contacts the fetal head, while the remaining 10% of the PVM lies above the inferior pubic ramus (Point “2,” Fig. 2) on either side of the valley not in

Fig. 2 Upper left: left lateral view of 3D model of the pelvis (green), showing the high origin location (arrow) of the PVM (orange) and the PVM insertion on the PB/AS (light blue). Upper right: 3D model of the pelvis (green), showing the PRM (dark purple, lower right of that image) originating from the PM (white). In the upper two figures, A, P, L, R, and I denote anterior, posterior, left, right, and inferior, respectively. Lower left: The pubic symphysis is projected in the sagittal view seen in a view from the left showing a downward rotation of the PVM loop. Note the wrapping of the PVM around the inferior pubic ramus at point 2 at ultimate crowning. The portion of the PVM between points 1 and 2 lying above the inferior pubic ramus point, 2, is the “noncontact” length because it cannot contact and encircle the fetal head due to the rigidity of the pubic bone. That part of the PVM lying between points 2 and 3 lies below the pubic ramus at 2 so it can contact and encircle the fetal head to allow it to pass inside the loop formed by the PVM. Lower right: This illustrates the downward rotation of the PRM from the prelabor to the ultimate crowning position. Note the absence of PRM wrapping.

contact with the fetal head. Then, as the PVM loop is drawn and rotated downward by the descending fetal head, the percentage of PVM length above Point 2 increases and the length in contact with the greater part of the fetal head decreases to $\sim 70\%$, because the valley is deeper. This means that the PVM will have to stretch more to accommodate the passage of the fetal head. The length of the PVM in contact with the head decreases (Fig. 2) because less of the loop can pass around in contact with the fetal head. In contrast, the full length of the PRM loop remains available to pass around the fetal head as it rotates downward because its origins lie close to the inferior pubic ramus.

Acquisition of Maternal MRI Data. MRI scans were acquired through the parent study “Evaluating Maternal Recovery from Labor and Delivery (EMRLD)” [11,12], which followed primiparous women after childbirth (Institutional Review Board approval # HUM00051193). In this article, we limit our consideration to subjects who served as controls and delivered via cesarean section, and who did not attempt to push prior to delivery. This was to ensure that our geometric model represents the female pelvic floor prior to the development of delivery induced injuries. The complete MRI protocol has been described elsewhere [11,12].

Maternal Capacity Model Generation. Axial, sagittal, and coronal images were imported into 3D SLICER 3.4.2009-10-15

(Brigham and Women’s Hospital, Boston, MA) imaging software. The segmentation editor module was used to create label maps of each feature. Label maps were based on the axial plane, but were traced using sagittal and coronal views as well. Anatomic features modeled include the anterior pelvis, PVM, PRM, perineal membrane (PM), and the AS.

Three-dimensional models were generated for three individuals (Fig. 2), and the individual closest to the 50th percentile was selected based on comparison to a previous 50th percentile model generated in our group [13]. Fiducial points were placed on visible PVM and PRM fibers identified in sagittal slices to establish their line-of-action [8]. These fiber lines were then extended until intersection with the pelvis (PVM) or PM (PRM) for origin identification and checked against the original scans to confirm anatomical plausibility. The posterior limit of these fibers was determined by extending their trajectory to the posterior-most point of the corresponding label map (Table 1).

The subpubic arch was calculated using the right and left PRM and PVM origins, as well as a midpoint placed on the pubic septum at the level of the origins. Pythagoras’ theorem was employed to calculate the distance between origins along the pelvis using the coordinates of these three points.

Maternal Capacity Calculations. In what follows, the calculations were all performed in Microsoft Excel.

Fig. 3 Caudal view of anterior pelvis with variables used in the maternal capacity calculations. The soft tissue loop originates high on the pelvis (filled arrow heads) and wraps around the fetal head (gray circular structure). The portion of the soft tissue loop in contact with the fetal head is represented by the thick black band, while the portion not in contact with the fetal head is represented by the dashed lines. θ = SPAA. Arch = pelvis/subpubic arch.

Anatomical Consideration

(1) SL

- It has been observed in rat models that muscle fiber length can increase by 37% during pregnancy in preparation for birth [14]. This architectural elongation was incorporated as a 1.37 fiber elongation (FE).
- The striated muscle stretch ratio, R_{SM} , may reach up to 1.6 prior to onset of injury [15].
- No human data are available on PM elastic properties, it is estimated that the PM stretch ratio, R_{PM} , is able to reach up to 1.15 based on data available for the abdominal fascia [16].
- The loops of tissue involve three main types of tissue. The PVM and PRM are striated muscle, and the AS complex has both smooth and striated muscle. PM and PB are primarily connective tissue.
 - The PRM loop takes origin bilaterally from a short length of passive fascia, called the PM, and passes anteroposteriorly as a right and left muscle portion that decussate posteriorly behind the rectum to form the anorectal angle. We assumed that the AS is able to deform prior to injury with the 1.6 striated muscle stretch ratio mentioned previously.
 - The PVM takes origin from the pubic bone bilaterally at bony entheses [17,18] and is comprised of striated muscle which inserts into the PB and smooth and striated muscle of the internal and external AS, respectively, in the intersphincteric groove, which is located between these sphincters (Fig. 2). Using the above assumptions, we calculate SL as follows:

$$\begin{aligned} SL_{PRM} &= FE * R_{SM} * L_{PRM} + R_{PM} * L_{PM} \\ &= \text{soft tissue loop length for PRM} \end{aligned} \quad (1)$$

$$\begin{aligned} SL_{PVM} &= FE * R_{SM} * L_{PVM} - L_{AS,PVM} + L_{AS,max} \\ &= \text{soft tissue loop length for PVM} \end{aligned} \quad (2)$$

(2) Maternal capacity in the ultimate crowned state

- We found that the PRM origin on the PM was so low that no wrapping of the PRM would occur about the inferior pubic rami in the downward rotation observed during birth.

Fig. 4 Graphic illustration of the sensitivity analyses in caudal view. Top: Nominal configuration using the convention in Fig. 3. Middle left: varying SL (thick black band). Middle right: varying soft tissue origin placement on pelvis (black arrow heads). Bottom left: varying SPAA. Bottom right: varying head size (gray circle). The variation in soft tissue length reduction in downward rotation is not shown. Factors were varied by $\pm 10\%$.

- The PVM origin lies approximately 2 cm below the pubic tubercle, necessitating up to 4 cm before it wraps around the pubic ramus on the left and right sides (distance between 1 and 2 on Fig. 2) [19].

$$\begin{aligned} C_{M,lower} &= SL + \pi * D_{head} * \left(\frac{180 - \theta}{360} \right) \\ &\quad - L_{wrap,left} - L_{wrap,right} \end{aligned} \quad (3)$$

This is termed the noncontact length because it reduces the muscle length available for contacting and accommodating the fetal head. The noncontact length was assumed to be a straight line. Accounting for curvature of the pelvis in this cut plane had less than a 1.5% effect on maternal capacity.

(3) Population variation

- The H-line, which is the distance from the inferior posterior aspect of the pubic symphysis to the posterior rectal wall, and which represents the anteroposterior width of the levator hiatus, has been quantified, with a mean of 4.4 ± 0.7 cm in 178 Caucasian women [20]. It is assumed here that percent variation in levator hiatus is proportional to variation in the SL.
- The retropubic arch angle, in a study of 593 individuals, has been reported to have a mean of 109.3 ± 9.0 deg when measured in the axial plane at the level of the PVM origins [21].
- A study of 178 women found a mean lower pelvis SPAA of 83.7 ± 7.0 deg [20].

Sensitivity analysis was performed by individually varying SPAA, SL, origin separation along pelvis, and the noncontact length (Fig. 4). Each variable was increased and decreased by 10%.

Fig. 5 Cranial and right side views of the fetal head showing the SD, MD, BD, and FD. Figure adapted from Sobre et al. [24].

The distribution of geometric maternal capacity values was calculated by incorporating the quantified variation in SPAA and H-line values discussed earlier in this section.

Part II: Quantification of Factors Affecting Fetal Head Demand

- (1) Approximating the suboccipitobregmatic circumference (SC) from the occipitofrontal circumference (OC)
 - (a) The Centers for Disease Control and Prevention has reported a mean male head circumference at birth of 344.6 mm and a mean female head circumference at birth of 338.8 mm [22,23]. These data refer to the OC, which is a function of the fronto-occipital (FD) and biparietal diameters (BD) (Fig. 5).
 - (b) The fetal head circumference that imposes the geometric demand on the pelvic floor during birth, the SC, is a function of the suboccipitobregmatic diameter (SD) and BD.
 - (c) Reduction of the BD and SD and corresponding elongation of the mentovertical (maxillovertical) diameter (MD) results from compressive forces experienced during labor [25].
 - (i) A fetal head MI for characterizing the degree of head deformation in the birth canal has been defined (Eq. (A16), Appendix), with a mean + SD value of 2.00 ± 0.22 observed clinically [26].
 - (d) As a simplification, we modeled the effective cross section of the fetal head as circular at the time of labor (BD = SD).

- (e) It was also assumed that the volume of the fetal head is constant.
- (f) An instantaneous increase in BD of at least 0.5 cm following birth has been observed [27]

$$\pi * BD_L = \frac{OC\sqrt{2}}{\sqrt{1 + \frac{MI}{1.2^2}}} - \frac{\pi}{2} \text{ cm} = \text{SC} \quad (4)$$

Functional fetal head circumferences were calculated for locations throughout reported population distributions for fetal head OC [13,14] and molding [6] (Fig. 6, and Supplemental Figure S1 is available under the “Supplemental Data” tab for this paper on the digital collection).

(2) Usual and abnormal fetal head presentations

- (a) The most common fetal head position during the second stage of labor, as the head is delivered, is an occiput anterior position or “vertex presentation,” with the back of the head oriented toward the pubic symphysis, and the nose toward the sacrum.
- (b) In a minority of births, the fetus presents in the occiput posterior or transverse position, with the nose oriented toward the pubic symphysis and the back of the skull toward the sacrum or placed sideways.
- (c) This change in position does not change the head circumference itself. But, it can, however, change the orientation of the head in the birth canal known as positional deflection of the head. The most extreme case of this deflection is a “face presentation” [28] in which the presenting diameter typically becomes 7 mm longer than that experienced during the vertex presentation [29]. In our simulations, a normal occiput anterior or vertex presentation was assumed

$$C_f = \sqrt{\frac{C_0^2 + (C_0 + \pi * 7 \text{ mm})^2}{2}} \quad (5)$$

Part III: Geometric Capacity-Demand Calculations Using the Value of g. A capacity-demand table for the values of g was created by using estimates of head size (SC) calculated for an average value of molding and using the minimum calculated maternal capacity for each population point which, interestingly, we shall see was always the PVM with wrapping value rather than the PRM value (cf. Figs. 7 and 8).

			fetal head circumference population distribution								
			2.30%	5%	10%	25%	50%	75%	90%	95%	97.70%
Molding population distribution	2.3%	-2	277	281	285	292	300	308	315	319	323
	5%	-1.65	271	275	279	286	294	301	308	312	316
	10%	-1.28	268	271	276	282	290	298	305	309	313
	25%	-0.68	263	266	270	277	285	292	299	303	307
	50%	0	257	261	265	272	279	286	293	297	301
	75%	0.68	252	256	260	266	273	281	287	291	295
	90%	1.28	248	252	255	262	269	276	282	286	290
	95%	1.65	245	249	253	259	266	273	280	283	287
	97.7%	2	241	245	248	255	261	268	275	278	282

Fig. 6 Vertex presentation. Male fetal head circumference (in mm) presenting to the birth canal in a vertex presentation. The shading (green) or the diagonal indicates a region of equal population distribution values for molding and head size. The intensity of the (blue) shading at lower left indicates the degree of maximal molding of small fetal heads, while the intensity of the (red) shading at upper right indicates the degree of lack of molding of large fetal heads.

Table 1 Variables used in the 3D SLICER analysis

Abbreviation	Description
L_{PRM}	Length of PRM, wrapped around rectum
L_{PM}	Distance between pelvis and PRM origin on PM
L_{PVM}	Combined length of PVM fibers, originating from pelvis and inserting on PB/AS
$L_{AS,PVM}$	Contact length between PVM and PB/AS at insertion
d_{AS}	Diameter of AS
t_{AS}	AS thickness
$L_{AS,max}$	Maximum length contribution of (PB/AS), calculated from d_{AS} and t_{AS}
$\delta_{origins,pelvis}$	Distance between origins along pelvis
θ	Subpubic arch angle
L_{wrap}	Distance between origin on pelvis and nearest PVM – head contact point

		DEMAND (Fetal Head Circumference, in Percentile)								
		2.3%	5%	10%	25%	50%	75%	90%	95%	97.7%
Circumference, in Percentile)	2.3%	0.67	0.66	0.65	0.63	0.62	0.60	0.59	0.58	0.57
	5%	0.78	0.77	0.76	0.74	0.72	0.70	0.69	0.68	0.67
	10%	0.90	0.89	0.87	0.85	0.83	0.81	0.79	0.78	0.77
	15%	0.97	0.96	0.94	0.92	0.90	0.88	0.85	0.84	0.83
	25%	1.08	1.06	1.05	1.02	0.99	0.97	0.95	0.93	0.92
	50%	1.26	1.25	1.22	1.20	1.16	1.14	1.11	1.09	1.08
	75%	1.44	1.42	1.39	1.36	1.32	1.29	1.26	1.24	1.23
	90%	1.59	1.56	1.54	1.50	1.46	1.43	1.39	1.37	1.36
	95%	1.67	1.65	1.62	1.58	1.54	1.50	1.47	1.45	1.43
	97.7%	1.75	1.73	1.70	1.66	1.61	1.58	1.54	1.52	1.50

Fig. 7 Predicted maternal capacity-to-fetal head demand ratio, g , for the PVM loop with wrapping. The intensity of the (red) shading indicates the degree of cephalolevator disproportion for the PVM.

		DEMAND (Fetal Head Circumference, in Percentile)								
		2.30%	5%	10%	25%	50%	75%	90%	95%	97.70%
Circumference, in Percentile)	2.30%	1.06	1.04	1.02	1.00	0.97	0.95	0.93	0.92	0.90
	5%	1.13	1.12	1.10	1.07	1.04	1.02	0.99	0.98	0.97
	10%	1.22	1.20	1.18	1.15	1.12	1.09	1.07	1.05	1.04
	15%	1.27	1.25	1.23	1.20	1.17	1.14	1.11	1.10	1.09
	25%	1.36	1.34	1.31	1.28	1.25	1.22	1.19	1.17	1.16
	50%	1.51	1.49	1.46	1.42	1.39	1.36	1.32	1.30	1.29
	75%	1.66	1.64	1.61	1.57	1.53	1.49	1.45	1.44	1.42
	90%	1.80	1.78	1.74	1.70	1.66	1.62	1.58	1.56	1.54
	95%	1.89	1.86	1.83	1.78	1.74	1.70	1.65	1.63	1.61
	97.70%	1.97	1.94	1.91	1.86	1.81	1.77	1.72	1.70	1.68

Fig. 8 Predicted maternal capacity-to-fetal head demand ratio, g , for the PRM loop. The intensity of (red) shading indicates the degree of cephalolevator disproportion for the PRM.

Results

Part I: Quantification of Factors Contributing to the Maternal Capacity for the 50th Percentile Woman. Maternal circumference values for the 50th percentile female at Ultimate Crowning were 425 mm for PRM and 313 mm for PVM (Table 2).

Our initial results assumed zero PB/AS deformation. We then investigated how reasonable geometric deformation of the PB/AS

Table 2 Effect of PVM wrapping on initial maternal capacities (in mm) for the 50th percentile female pelvis at ultimate crowning

	Circumference	Diameter
PRM loop	425	135
PVM without wrapping	347	110
PVM with wrapping	313	100

(Supplemental Figure S1 is available under the “Supplemental Data” tab for this paper) would contribute to maternal capacity to accommodate birth without injury (Table 3). We began with the shape deformation of the PB/AS from a circular sphincter to an elliptical cross section with corresponding stretch of the PB resulting from lateral tension, without changes in cross-sectional area or wall thickness. This resulted in a maternal capacity increase to 326 mm for PVM. A $1.6 \times$ stretch without injury of the smooth muscle lining comprising the PB/AS resulted in a further increase in maternal capacity to 349 mm for PVM. All subsequent results follow from a model with PB/AS shape deformation and $1.6 \times$ muscle stretch.

Results for the sensitivity analysis (Table 4) showed that a 10% change in subpubic angle resulted in up to a 4% decrease or a 2% increase in circumference. Further, varying SL by 10% resulted in up to a 15% change in maternal capacity for the PVM loop. The same 10% change in SL resulted in up to an 8% change in circumference for the PRM loop. Likewise a 10% change in origin separation along the pelvis allowed for a 2% change in

Table 3 Effect of incorporating PB/AS shape deformation and soft tissue stretch on maternal capacity (in mm) in the presence and absence of PVM wrapping about the inferior pubic ramus (see Fig. 2)

	No shape deformation	Shape deformation only	Shape deformation + soft tissue stretch
PVM without wrapping	347	357	374
PVM with wrapping	313	326	349

Table 4 Results of the sensitivity analyses (expressed as a percentage change in maternal circumference) for the four factors in the presence and absence of PVM wrapping

	PRM (%)	PVM without wrapping (%)	PVM with wrapping (%)
SPAA (−10%)	−3	−2	−4
SPAA (+10%)	+2	+1	+2
SL (−10%)	−8	−9	−15
SL (+10%)	+8	+9	+15
Origin separation along pelvis (−10%)	−2	−1	−2
Origin separation along pelvis (+10%)	+2	+1	+2
Noncontact length (−10%)	0	0	+5
Noncontact length (+10%)	0	0	−5

Table 5 Distribution of maternal geometric capacities (in mm) calculated with and without PVM wrapping about the inferior pubic rami

Maternal percentile	PRM loop	PVM without wrapping	PVM with wrapping
2.3	292	259	185
5	313	279	216
10	336	300	248
15	351	314	269
25	374	334	298
50	416	372	349
75	458	409	397
90	497	443	438
95	521	464	462
97.7	543	483	484

circumference. Only two factors affected PVM circumference calculations: noncontact length and head diameter. A 10% change in noncontact length resulted in up to a 5% change in circumference. So, the factors with the greatest effect on maternal capacity were initial SL, downward bending angle, and narrowing of the SPAA, in that order.

Based on variations in SPAA and SL, the distribution in maternal capacity was calculated (Table 5). The 50th percentile female had a capacity of 416 mm for PRM and 349 mm for PVM. The 2.3rd percentile female had a capacity of 292 mm for PRM and 185 mm for PVM. The 97.7th percentile female had a capacity of 543 mm for PRM and 484 mm for PVM.

From Tables 2 and 3, we see that it is the PVM that is the levator structure that most constrains maternal geometric capacity after having rotated downward into its most inferior position at the end of the second stage. This finding corroborates and extends the results of Lien et al. who used a similar, but less accurate, site of PVM attachment on the pubic bone and who did not consider the downward rotation of the PVM in their analysis [1].

Part II: Quantification of Factors Affecting Fetal Head Demand. Calculation of fetal head demand (SC) for population values of OC and MI revealed a SC value of 300 mm for a male head with 50th percentile molding and 50th percentile OC (Fig. 6). Male fetuses having the same percentile value for both head size and molding (small head with very little molding, medium head with medium molding, and large head with maximum

molding) (shaded (green) diagonal, Fig. 6) ranged in SC value from 297 to 302 mm. A male head of minimum OC and maximum MI had a SC value of 257 mm, while a male head of minimum MI and maximum OC had a SC value of 351 mm. Values were slightly lower for female heads (see Appendix).

The 7 mm diameter increase that has been reported to occur with face presentation increased the predicted effective circumference by 11 mm (Fig. 9).

Part III: Capacity-Demand Calculations Using the Value of g. Here, we consider the fetal head demand results from Part II within the context of the maternal capacity results from Part I by tabulating the population values of g. For the PVM loop, fetal head demand (SC) was predicted to exceed maternal capacity for every maternal capacity smaller than the 10th percentile. The 25th percentile maternal capacity met the demands represented by the 25th percentile fetal head, and was approximately equal to the demand imposed by the 50th percentile fetal head. The 50th percentile maternal capacity was predicted to be able to deliver all fetal head sizes examined without injury (Fig. 7).

For the PRM loop, fetal head demand was predicted to be satisfied by all maternal capacities greater than the 5th percentile. The 5th percentile maternal capacity was predicted to satisfy up to the 75th percentile fetal head demand. Maternal capacities of 10th percentile and above were predicted to suffice for any fetal head size (Fig. 8).

Similar results were obtained for the other two women whose models were derived from the MR scans.

Discussion

Part I: Quantification of Factors Contributing to the Maternal Capacity for the 50th Percentile Woman. The sensitivity analysis showed that initial SL had the largest impact on circumference. In particular, the increase in SL allows the head–pelvis contact points to move farther posteriorly and laterally along the pelvis, increasing the pelvis–head arch length in addition to the portion of the circumference comprised by the SL. In the case of the PVM, the 10% change in SL that results in a 15% change in maternal capacity is a result of the noncontact PVM length remaining constant, allowing all of the gained length to contribute directly to encompassing the fetal head. SL had the greatest impact on maternal capacity, followed by SPAA, which was closely followed by origin separation. In the PVM model, noncontact length had less of an effect than initial SL itself, but a greater effect than any other factor considered here.

			fetal head circumference population distribution								
			2.30%	5%	10%	25%	50%	75%	90%	95%	97.70%
Molding population distribution	2.3%	-2	288	292	296	304	311	319	326	331	335
	5%	-1.65	282	286	290	297	305	312	319	323	327
	10%	-1.28	279	283	287	294	301	309	316	320	324
	25%	-0.68	274	278	282	288	296	303	310	314	318
	50%	0	268	272	276	283	290	297	304	308	312
	75%	0.68	263	267	271	278	285	292	298	302	306
	90%	1.28	259	263	267	273	280	287	294	297	301
	95%	1.65	257	260	264	270	277	284	291	295	298
	97.7%	2	252	256	260	266	273	280	286	289	293

Fig. 9 Face presentation. Male fetal head circumference (in mm) presenting to the birth canal during face presentation. The shading (green) of the diagonal indicates a region of equal population distribution values for molding and head size. The intensity of the (blue) shading at lower left indicates the degree of maximal molding of small fetal heads, while the intensity of (red) shading at upper right indicates the degree of lack of molding of large fetal heads.

Part II: Quantification of Factors Affecting Fetal Head Demand. Population values of SC varied from 253mm for a female head of minimum OC and maximum MI to 351 mm for a male head of maximum OC and minimum MI. However, male fetuses having the same percentile value for OC and MI (shaded (green) diagonal, Fig. 6) ranged in SC value from 297 to 302 mm, varying by a maximum of 5 mm. As molding is the consequence of compressive forces, and the compressive forces experienced would be expected to increase with head size, it is feasible that the greatest extent of molding would occur in the largest heads. However, it is also possible that the smallest heads would be the least developed structurally and therefore the most susceptible to deformation for a given compressive force.

The 0.7 cm diameter increase reported to occur with face presentation increased the effective circumference by 11 mm. For a mother delivering a baby close to her capacity, this could make the difference between safe delivery and a life time of complications following levator injury. It has also been previously proposed that the increase in injuries associated with occiput posterior presentation is the result of increased soft tissue resistance and poor use of the bony birth canal space during this type of delivery [30].

Part III: Capacity-Demand Calculations Using the Value of g . The approach in this paper provides a new framework for considering the biomechanical reasons for maternal levator injury during vaginal delivery by relating fetal demand to maternal capacity via a simple ratio, g . The Part III values of g reveal that a 50th percentile maternal capacity can accommodate fetal heads of all sizes, a 25th percentile maternal capacity will accommodate half of all fetal head sizes, and a 15th percentile maternal capacity is insufficient to accommodate any fetal head sizes without any creep-relaxation behavior. These tissue properties are indeed known to be time dependent, with increases in compliance observed during late pregnancy [31,32], which may provide the additional soft tissue lengthening of 8% necessary for the 15th percentile female to be able to deliver a head of average size. Alternatively, we may have underestimated the amount of molding that occurs acutely, since most measurements of molding are made post-hoc at time intervals of 1 hr or more after the baby is delivered. They do not capture the situation while the head is in the pelvic cavity. The fetal skull is viscoelastic [27,33,34], so a certain degree of spring-back may have already occurred before the first measurement of fetal skull size is made in the delivery room [27]. If the amount of molding has been underestimated by 50%, then the average fetal head circumference presented to the pelvic floor would be 279 mm, with minimum and maximum values of 241 mm and 323 mm, respectively, or a reduction in fetal head circumference by approximately 7%.

Our geometric model provides the first biomechanical explanation for why the PVM is more likely to be injured during childbirth than the PRM (see “Introduction” section). A 10th percentile woman’s PRM can accommodate any fetal head demand, while a 25th percentile woman’s PVM can only accommodate the demand represented by half of all fetal heads. It has not been immediately intuitive why the PVM should be more constrained than the PRM. The answer is found in the location of their origins on the pelvis. We found that the PRM origin on the PM was so low that PRM–pelvis wrapping could not occur in the downward rotation observed during birth. In contrast, the PVM origin is approximately 2 cm below the pubic tubercle, necessitating up to 4 cm in PVM–pelvis wrapping per side (8 cm total) [19]. Since this distance is required for wrapping around the pubic bone, it reduces the PVM muscle length available for accommodating the fetal head. Clearly, the greater the perineal descent which, for a given head size, would be expected to be exacerbated by less elastic soft tissues and less creep relaxation, the higher the probability of PVM wrapping.

Might Ultrasound Be Used to Assess PVM Injury Risk? If acquired prior to labor, as demonstrated in the case of BD and head circumference by Ergaz et al. [35], measurement of the fetal head diameters (MD, SD, and BD) would allow for calculation of the fetal head size relative to the population and relative to the mother’s injury threshold. So

$$\begin{aligned} \text{Fetal Head Volume} &= \frac{1}{6} \pi MD_0 * BD_0 * SD_0 \\ &= \frac{1}{6} \pi MD_f * BD_f * SD_f = \frac{1}{6} \pi MD_f * BD_f^2 \end{aligned} \quad (6)$$

The fetal head volume and MI can be simplified using the assumption $BD = SD$

$$MI = \frac{MD_f^2}{BD_f^2} \quad (7)$$

$$MD_f = \sqrt{MI} * BD_f \quad (8)$$

This allows us to express MD_f and as a result fetal head volume as a function of BD_f

$$MD_0 * BD_0 * SD_0 = MD_f * BD_f^2 = \sqrt{MI} * BD_f^3 \quad (9)$$

$$BD_f = \frac{(MD_0 * BD_0 * SD_0)^{1/3}}{MI^{1/6}} \quad (10)$$

		DEMAND (Fetal Head Circumference, in Percentile)								
		2.3%	5%	10%	25%	50%	75%	90%	95%	97.7%
Circumference, in Percentile)	2.3%	0.94	0.93	0.91	0.89	0.86	0.84	0.82	0.81	0.80
	5%	1.01	1.00	0.98	0.96	0.93	0.91	0.89	0.87	0.86
	10%	1.09	1.07	1.05	1.03	1.00	0.98	0.95	0.94	0.93
	15%	1.14	1.12	1.10	1.08	1.05	1.02	1.00	0.98	0.97
	25%	1.21	1.19	1.17	1.14	1.11	1.09	1.06	1.05	1.03
	50%	1.35	1.33	1.31	1.27	1.24	1.21	1.18	1.17	1.15
	75%	1.48	1.46	1.44	1.40	1.36	1.33	1.30	1.28	1.27
	90%	1.61	1.58	1.55	1.52	1.48	1.44	1.41	1.39	1.37
	95%	1.68	1.66	1.63	1.59	1.55	1.51	1.47	1.45	1.44
	97.7%	1.75	1.73	1.69	1.65	1.61	1.57	1.53	1.51	1.50

Fig. 10 Predicted maternal capacity-to-fetal head demand ratio, g , for the PVM loop *without* wrapping. The intensity of the (red) shading indicates the degree of cephalolevator disproportion for the PVM in this special case.

As a result, we can solve for BD_f and SC in terms of prelabor fetal head measurements

$$SC = \pi * BD_f = \pi \frac{(MD_0 * BD_0 * SD_0)^{1/3}}{MI^{1/6}} \quad (11)$$

From Fig. 7, we see that it is more important to measure maternal capacity than the fetal head demand. It is only in the region between the 15th and 25th percentile that additional insight may be gained by measuring the fetal head. It may not yet be feasible to acquire origin locations and specific PVM and PRM geometries via ultrasound. However, SPAA and hiatus width are regularly quantified via ultrasound and can be used to identify a mother's status within the population [20,36]. Even without fetal head measurements, these data could then be used to identify mothers who are on the border between predicted labor success and predicted cephalolevator muscle disproportion. This would equate to the situation of encountering a value of g slightly less than 1.0. In this situation, interventions such as antenatal perineal massage might be employed to try to prevent trauma at the time of labor [37]. In terms of clinical applicability, the capacity-demand ratio, g , that we have calculated could be used by clinicians to assess injury risk in the same way calculators are currently used to assess likely success with vaginal birth after cesarean delivery [38]. Ultimately, the goal here is to provide mothers and practitioners with information of levels of risk so that they can make better informed decisions during their labor preparation process. A woman with a very low g ratio and anticipating only one child might, for example, choose cesarean delivery before labor. At present, cesarean section on maternal request is often selected because of concerns for pelvic floor injury without knowing how likely that injury is to occur.

This analysis has a series of limitations, some of which are the result of current knowledge gaps and some of which are due to simplifying assumptions. First, in the Part I maternal capacity calculations, the lack of in vivo viscoelastic data for the human LA muscle during vaginal delivery currently limits any accurate prediction of time-dependent PVM and PRM muscle loop behavior. This means the present maternal capacity calculations are conservative because time-dependent creep relaxation behavior would lead to larger maternal capacity values than presently calculated. The viscoelastic behavior has been measured in vitro in rat and human vaginal tissue by Jing [31] and by Lowder et al. in rat vaginal tissue [32]. Jing found a relaxation behavior with time constants on the order of 31 and 40 min in pregnant and nonpregnant rats, respectively. If these apply to the PVM loop, and there is no evidence yet that they do, then in a 1–2-hr time window, representing the average length of the second stage of labor, one would expect to see noticeable creep lengthening of the PVM. In practice, a final stretch ratio of 1.73 after creep would be required for the 15th percentile female to be able to deliver 50% of all fetal

heads, resulting in the observed injury occurrence of approximately 13% [4].

Might it be possible that assumptions made in this analysis biased the results? The assumption for which we do not have direct experimental evidence is the wrapping of the PVM around the inferior margin of the pubic ramus as the PVM loop rotates downward during the second stage of labor (Fig. 2). This assumption causes the effective length of the PVM to be shortened, thereby increasing the amount of PVM stretch required. If this wrapping does not occur, then we will have overestimated the stretch of the PVM, but not the PRM (Fig. 10). That overestimation for PVM stretch is tabulated in Tables 2, 3, 5, and S1 (Supplemental Table S1 is available under the “Supplemental Data” tab for this paper). Additionally, we have made the assumption that muscle FE observed in rats during pregnancy also occurs in humans. As human studies on this question have not been conducted, and as there is not a perfect analog between rat and human pelvic floor anatomy, we have made the assumption that the rat coccygeus muscle is the closest analog to human LA muscles.

A limitation in the Part II fetal head demand analysis is the lack of measurements of the spring-back of the fetal head skull in the minutes after delivery and before the fetal head is measured. This means we may have underestimated the effect of molding in our calculations. Greater molding would lead to a diminished fetal head demand and therefore a larger g value than presently predicted, so again our analysis is conservative. Variations in fetal head shape, such as the noncircular cross section observed in occiput posterior presentation, and subsequent shape changes in passage along the Curve of Carus are also expected to have an impact and should be considered in future models.

There is already evidence that pelvic floor measurements can help predict delivery outcome. In a study of 231 nulliparous women, Siafarikas et al. found that smaller levator hiatus dimensions measured by ultrasound in late pregnancy had a significant association with a longer active second stage of labor and increased likelihood of the need for instrumental delivery to complete delivery [39]. It seems logical that these weak correlations (all < 0.3) can be strengthened once the other measureable parameters such as head size and SPAA are added. The theoretical framework provided in this article to organize the key geometrical factors influencing maternal capacity and fetal demand should help in the process of identifying elements that can be used for more accurate predictions and should help guide future work in this direction.

Conclusions

- (1) Initial SL had the greatest impact on maternal capacity, followed by noncontact length, then SPAA, and finally levator origin separation.

- (2) We conclude that the PVM and PRM loops have the capacity to accommodate 75% of births vertex presentation without injury. But for injury to occur in only 15% of births, as observed clinically, there must be either more fetal head molding than was allowed for, or creep relaxation behavior of the PVM loop under strain, both of which are entirely possible.
- (3) We conclude that the more caudal origin of the PRM portion of the levator muscle reduces its stretch ratio at ultimate crowning, thereby helping to protect it from the stretch injuries commonly observed in the PVM portion.
- (4) Use of ultrasound to measure fetal head diameter prior to birth could provide information on the fetal head demand that will be made of the maternal LA muscles, and hence g , during birth. Ultrasound estimates of levator hiatus size prior to birth would provide a first estimate of maternal capacity via initial SL.
- (5) The numeric value of the capacity—demand ratio, g , indicates the level of risk for levator injury during the late stage of vaginal delivery. A g value of 1.0 or more rules out cephalolevator muscle disproportion and hence risk of levator injury due to the conservative assumptions employed in the current analysis.
- (6) In practice, it may be most logical to first measure maternal capacity in order to establish whether it lies above the 25th percentile. If it lies below the 25th percentile, then the fetal head should be measured to gain the additional insight provided by the value of g .

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Nomenclature

See also Table 1.

AS	= anal sphincter
BD	= biparietal diameter
BD _f	= BD following molding
BD _L	= BD at time of labor
BD ₀	= BD prior to molding
C _f	= face presentation circumference
C _{M, lower}	= maternal circumference in the ultimate crowning state
C ₀	= original circumference
D _{head}	= fetal head diameter
FD	= fronto-occipital diameter
FE	= fiber elongation
LA	= levator ani
MD	= mentovertical diameter
MD _f	= MD following molding
MD ₀	= MD prior to molding
MI	= molding index
OC	= occipitofrontal circumference
PB	= perineal body
PM	= perineal membrane
PRM	= puborectal muscle
PVM	= pubovisceral muscle
R _{PM}	= perineal membrane stretch ratio
R _{SM}	= striated muscle stretch ratio
SC	= suboccipitobregmatic circumference
SD	= suboccipitobregmatic diameter
SD _f	= SD following molding
SD ₀	= SD prior to molding
SL	= soft tissue loop length
SL _{PRM}	= soft tissue loop length for PRM
SL _{PVM}	= soft tissue loop length for PVM
SPAA	= subpubic arch angle

Appendix

Due to the small sample size and the nature of the parent study, both subjects 2 and 3 were below the 50th percentile in size. Results reported in Table S1 (Supplemental Table S1 is available under the “Supplemental Data” tab for this paper) assume no soft tissue stretch or shape deformation of the AS.

SPAA: as measured at the ischium of the pelvis

Retropubic arch angle: as measured in the axial plane found once the full length of the pubic rami is visible after drawing a perpendicular plane through the pubic symphysis [21].

Levator Hiatus: measured as the H-line, or the distance from the inferior posterior aspect of the symphysis to the posterior rectal wall [20].

A.1 Calculations

A.1.1 Calculating SL

$$SL_{PRM} = FE * R_{SM} * L_{PRM} + R_{PM} * L_{PM} \quad (A1)$$

where SL_{PRM} is the soft tissue loop length for PRM, L_{PRM} is the length of PRM, wrapped around rectum, and L_{PM} is the distance between pelvis and PRM origin on PM

$$SL_{PVM} = FE * R_{SM} * L_{PVM} - L_{AS,PVM} + L_{AS,max} \quad (A2)$$

where SL_{PVM} is the soft tissue loop length for PVM, L_{PVM} is the combined length of PVM fibers, originating from pelvis and inserting on PB/AS, $L_{AS,PCM}$, is the contact length between PVM and PB/AS at insertion and $L_{AS,max}$ is the maximum length contribution of PB/AS.

The area of the internal AS was calculated by subtracting the rectal space from the circular cross section defined by the circumference of the PB/AS

$$A_{AS} = \pi \frac{d_{AS}^2}{4} - \frac{\pi}{4} (d_{AS} - 2 * t_{AS})^2 \quad (A3)$$

where d_{AS} is the diameter of AS and t_{AS} is the AS thickness

$$d_{AS,min} = 2 * t_{AS} \quad (A4)$$

After evacuation of the rectum, the PB/AS can be reconfigured as an ellipse with conserved cross-sectional area and ring thickness (Supplemental Figure S1 is available under the “Supplemental Data” tab for this paper)

$$A_{AS} = \frac{\pi}{4} d_{AS,max} * d_{AS,min} \quad (A5)$$

The maximum diameter of the PB/AS can be solved for in terms of original diameter and ring thickness

$$d_{AS,max} = \frac{2 * A_{AS}}{\pi * t_{AS}} = \frac{(d_{AS}^2 - (d_{AS} - 2 * t_{AS})^2)}{2 * t_{AS}} \quad (A6)$$

After elliptical distortion, PB/AS muscle fibers run approximately linearly along the long diameter, allowing for a 1.6× stretch without injury (Supplemental Figure S2 is available under the “Supplemental Data” tab for this paper on the digital collection)

$$L_{AS,max} = R_{SM} * d_{AS,max} \quad (A7)$$

A.1.2 Maternal Circumference in a Single Plane

$$C_M = SL + AL_{head,pelvis} - L_{NC} \quad (A8)$$

where C_M is the maternal circumference, $AL_{head,pelvis}$ is the arch length along head, between contact points with the pelvis, and L_{NC} is the soft tissue loop length not in contact with fetal head

(Supplemental Figure S3 is available under the “Supplemental Data” tab for this paper on the digital collection)

$$L_{NC} = 2 * L_{head,pelvis} - \delta_{origins,pelvis} \quad (A9)$$

where $\delta_{origins,pelvis}$ is the distance between origins along pelvis and $L_{head,pelvis}$ is the distance from origin of pelvis angle to head–pelvis contact point

$$L_{head,pelvis} = \frac{D_{head}}{2 * \tan\left(\frac{\theta}{2}\right)} \quad (A10)$$

where $D_{head} = BD = SD = \text{fetal head diameter}$ and θ is the subpubic arch angle (deg)

$$AL_{head,pelvis} = \pi * D_{head} * \left(\frac{180 - \theta}{360}\right) \quad (A11)$$

$$\begin{aligned} C_M &= \pi * D_{head} \\ &= SL + \pi * D_{head} * \left(\frac{180 - \theta}{360}\right) + \delta_{origins,pelvis} - \frac{D_{head}}{\tan\left(\frac{\theta}{2}\right)} \end{aligned} \quad (A12)$$

$$C_M = \pi * D_{head} = \frac{SL + \delta_{origins,pelvis}}{1 + \frac{\theta - 180}{360} + \frac{1}{\pi \tan\left(\frac{\theta}{2}\right)}} \quad (A13)$$

A.1.3 Maternal Circumference in the Lower Plane

$$C_{M,lower} = SL + \pi * D_{head} * \left(\frac{180 - \theta}{360}\right) - L_{wrap,left} - L_{wrap,right} \quad (A14)$$

where L_{wrap} is the distance between origin on pelvis and nearest PCM–head contact point.

It was necessary to assume a value for fetal head diameter in order to solve for L_{wrap} .

A.2 Fetal Head Calculations

A.2.1 Approximating the SC From the OC. The SC results from an ellipse with the BD and SD as its axes (Fig. 5). This was simplified by approximating SD to be equal to BD

$$SC \approx \pi \sqrt{\frac{SD^2 + BD_L^2}{2}} = \pi * BD_L \quad (A15)$$

where BD_L is the biparietal diameter during labor.

Kriewall’s MI was modified by approximating SD to be equal to BD, and by approximating the MD to be equal to $1.2 * FD$, based on values reported by Sobre et al. [24,26]

$$MI = \frac{MD^2}{BD_B * SD} = \frac{1.2^2 FD^2}{BD_B^2} = 2.0 \pm 0.22 \quad (A16)$$

where BD_B is the biparietal diameter post–birth

$$FD^2 = \frac{MI * BD_B^2}{1.2^2} \quad (A17)$$

The OC (conventional measurement taken at time of birth) is a function of FD and BD. Equation (A16) was solved for FD (A17), which was used to solve for OC in terms of MI and BD (A18)

$$OC \approx \pi \sqrt{\frac{FD^2 + BD_B^2}{2}} = \pi * BD_B \sqrt{\frac{\left(1 + \frac{MI}{1.2^2}\right)}{2}} \quad (A18)$$

Equation (A18) leads to the ability to write BD as a function of OC and MI, which are both commonly reported

$$BD_B = \frac{OC \sqrt{2}}{\pi \sqrt{1 + \frac{MI}{1.2^2}}} \quad (A19)$$

It has been observed that BD increases by at least 0.5 cm between labor and measurements taken immediately after birth [27]

$$BD_L = BD_B - 0.5 \text{ cm} \quad (A20)$$

Equations (A19) and (A20) allow us to solve for BD_L , and consequently SC as a function of commonly reported variables

$$\pi * BD_L = \frac{OC \sqrt{2}}{\sqrt{1 + \frac{MI}{1.2^2}}} - \frac{\pi}{2} \text{ cm} = SC \quad (A21)$$

A.2.2 Face Presentation. The face presentation circumference (C_f) was calculated as the circumference of an ellipse with one axis as the unaltered circumference (d_0) and one axis as the modified diameter (d_f), observed to gain up to 7 mm at delivery. Both diameters were expressed in terms of the original circumference (C_0), allowing us to calculate C_f as a function of C_0 only (Fig. 9).

$$C_f = \pi \sqrt{\frac{d_0^2 + d_f^2}{2}} \quad (A22)$$

$$d_0 = \frac{C_0}{\pi} \quad (A23)$$

$$d_f = d_0 + 7 \text{ mm} \quad (A24)$$

$$C_f = \pi \sqrt{\frac{\frac{C_0^2}{\pi^2} + \left(\frac{C_0}{\pi} + 7 \text{ mm}\right)^2}{2}} \quad (A25)$$

$$C_f = \sqrt{\frac{C_0^2 + (C_0 + \pi * 7 \text{ mm})^2}{2}} \quad (A26)$$

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