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Biomechanical Analyses of the Efficacy of Patterns of Maternal Effort on Second-Stage Progress

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Abstract

OBJECTIVE—To develop and use a biomechanical computer model to simulate the effect of varying the timing of voluntary maternal pushes during uterine contraction on second-stage labor duration.

METHODS—Published initial pelvic floor geometry was imported into technical computing software to build a simplified 3-D biomechanical model with six representative viscoelastic levator muscle bands interconnected by a hyperelastic iliococcygeal raphé. An incompressible sphere simulated the molded fetal head. Forces from uterine contraction and voluntary expulsive efforts were summed to push the model fetal head along the Curve of Carus opposed by the resistance of the pelvic floor structures to stretch. Holding uterine maximal contraction force and push strength constant, pushes were timed before (“Pre”), at (“Peak”), and after (“Post”) maximal uterine contraction force. The effect of different combinations of pushes on second stage duration and the number of pushes required for delivery were evaluated.

RESULTS—Calculated second stage durations ranged from 57.5 minutes (“triple” or Pre-Peak-Post pattern) to 75.8 minutes (“pre-push” and “post-push” patterns). Delivery with the “triple push” pattern required 59 voluntary pushes, while the “peak push” pattern required 23 voluntary pushes, a 61% reduction. The corresponding reduction for the “pre-and-peak push” pattern was 29%, the “peak-and-post push” pattern was 30%, the “pre-push” pattern was 54%, and the “post-push” pattern was 56%.

CONCLUSION—Although the “triple push” pattern resulted in a 16% shorter second stage, this came at the energetic expense of a 61% increase in the number of pushes required.

Introduction

During the second stage of labor, women augment the force of uterine contractions by bearing down. They are often instructed to begin pushing soon after contraction onset and to make sustained efforts to continue until the contraction wanes.⁽¹⁾ Although the pattern of pushing varies, this typically results in one push before, one during and one after peak uterine contraction force. In contrast, when women push spontaneously, they do not initiate the bearing down effort until near the middle of the uterine contraction, with most effort directed at contraction peak.⁽¹⁾ Several studies have started to explore the biomechanics of

pushing during the second stage. These include factors that affect intrauterine pressure during pushing and the amplitude of intercostal muscle myoelectric signal, (2–3) but the theoretical effects of different pushing patterns remains unclear.

Pushing requires significant maternal effort to be expended during the second stage. The mean second stage duration in nulliparous women has been reported as 70 minutes, with 27% of patients having a second stage duration exceeding 2 hours.(4) During prolonged labor, some women become so exhausted that they cannot generate sufficient force to deliver without instrumented assistance with forceps or vacuum; interventions that can pose potential complications for mother and fetus.(5,6) Therefore understanding factors that might reduce maternal exhaustion may lead to a higher likelihood of spontaneous delivery and reduction of potential fetal or maternal injury.

The goal of this theoretical study, therefore, was to estimate how different patterns of maternal effort might affect progress during the second stage of labor. We developed a biomechanical model to simulate the second stage of labor such that the efficacy of different patterns of maternal effort could be quantitatively compared and analyzed.

Methods

The initial geometry of female pelvic floor at the beginning of the second stage of labor was based on magnetic resonance (MR) images of a healthy woman taken from an earlier study (Figure 1A).(7) Using this MR geometry a simplified 3-D biomechanical model was then developed in Matlab™ (The MathWorks, Natick, MA) and solved using its Simulink software (Figure 1B). Six levator ani muscle bands were used to represent the iliococcygeal, pubovisceral and puborectal portions of the levator ani muscle (Figure 1C). The muscle bands were simulated by U-shaped viscoelastic slings wrapped around the fetal head to form the birth canal and were interconnected by springs representing the iliococcygeal raphe (Figure 1C). The material properties of these structures are described in more detail later in this section.

After taking into account the 10% reduction in size resulting from the effect of molding,(8) the premolded fetal head was simulated with a 9 cm diameter rigid sphere representing the 50th percentile fetal head.(9) During the simulation, the fetal head was constrained to move along a specific trajectory given by the dashed line in Figure 1D which represents the Curve of Carus. As a first-order approximation, the body of the fetus was neglected, and the fetal head was considered to carry the whole inertial mass of the fetus.

The time history profiles of the intrauterine pressure and the pressure on fetal head during the second stage of labor were taken from the literature.(10,11) Rempen showed that the mean pressure on the fetal head in the amniotic cavity was 8.5 kPa during a uterine contraction, while a voluntary push increased the pressure to 19 kPa. The average basal tone during the rest interval was 2.6 kPa.(10) As a first-order approximation, the expulsive force was simulated by applying uniform expulsive pressure to the “cranial” hemisphere of the fetal head, the equator of which was constrained to lie perpendicular to the Curve of Carus as the head progressed through the pelvic floor. The Curve of Carus was defined as a locus of points lying 6 cm dorsal to the posterior margin of the pubic symphysis (Figure 1D). The resulting expulsive pressure was integrated and applied as a force to move the fetal head along its path of progression during labor (see below).

Maternal behavior during the directed pushing was implemented as described in the literature.(11,12) In directed pushing the birthing mother is commonly asked to begin pushing when the coach senses a uterine contraction has started, being asked to hold the effort for 10 seconds, to take a rest and resume the effort. Therefore, we simulated directed

pushing by superposing three 10-second voluntary pushes timed to occur at 25%, 50% and 75% of the uterine contraction duration (Figure 2A). In contrast, during spontaneous pushing, the maternal “bearing down” efforts occur when each uterine contraction is well established. Spontaneous pushing was therefore simulated with one voluntary push timed at the contraction peak (Figure 2B). The duration of the uterine contraction and the duration of the rest interval between two contractions were set to be 1 and 2 minutes, respectively. Other possible voluntary pushing patterns during birth were also simulated including double voluntary pushes timed at 25% and 50% of the uterine contraction duration, double voluntary pushes timed at 50% and 75% of the uterine contraction duration, a single voluntary push occurring before the peak uterine contraction duration, and a single voluntary push occurring after the peak uterine contraction duration (Figure 2C~2F).

The resistance to progress met by the fetal head is largely due to the resistance of the levator muscle bands to stretch. The resistance of each muscle band to stretch was represented mathematically by a five-parameter, viscoelastic model, consisting of a spring in series with two Kelvin-Voigt element. The constitutive equation of the muscle was

$$\begin{aligned} \mu_1\mu_2\ddot{\sigma} + (E_0\mu_1 + E_0\mu_2 + E_1\mu_2 + E_2\mu_1)\dot{\sigma} + (E_0E_1 + E_0E_2 + E_1E_2)\sigma \\ = E_0\mu_1\mu_2\ddot{\varepsilon} + (E_0E_1\mu_2 + E_0E_2\mu_1)\dot{\varepsilon} + E_0E_1E_2\varepsilon \end{aligned}$$

where E_0 , E_1 , E_2 were the elastic parameters and μ_1 , μ_2 were viscosity coefficient, σ and ε denote stress and strain, respectively, and their first and second time derivatives (dot and double dot notation, respectively). This equation states that levator muscle stress (defined as tensile force in the muscle divided by muscle cross-sectional area) and strain (increase in length divided by initial length), and their derivatives (i.e., rates of change over time) are related by a series of terms involving the elastic and/or viscous behavior of the muscle in tension. The stress-strain equation of the hyperelastic ligament spring was

$$\sigma = A \cdot (e^{B\varepsilon} - 1)$$

where A , B are the material constants. This equation states that the tensile resistance to muscle stretch increases exponentially with elongation. Because no material properties of the human levator ani muscle are published, their properties were assumed to be represented by published properties for the pregnant human cervix (13) whose palpated ripening parallels that observed in pelvic floor tissues. The parameters of the material properties used for the levator muscle bands are shown in Table 1.

The expulsive force was assumed to be evenly distributed on the cranial half of the sphere representing the fetal head, so it was integrated and represented by concentrated force acting at the center of the sphere. An additional normal force was applied at right angles to the path of progression to constrain the fetal head to move along the trajectory of Curve of Carus. The movement of the fetal head was then calculated from the equations of the motion:

$$\begin{aligned} M\ddot{X} &= F\cos(\alpha) + N\cos(\alpha - \frac{\pi}{2}) + \sum_i Nm_i\cos(\theta_i) \\ M\ddot{Y} &= F\sin(\alpha) + N\sin(\alpha - \frac{\pi}{2}) + \sum_i Nm_i\sin(\theta_i) \end{aligned}$$

where X and Y were the position of the center of the fetal head, M was the mass of the fetal head, F was the expulsive force, N was the normal force, and Nm_i represented the equivalent

reaction force from each muscle band (Figure 1D). This is the application of Newton's Second law: $F=ma$.

The progress of the fetal head descent during the second stage of labor was then computed with respect to different voluntary push profiles. The time histories of the change in levator ani muscle stretch ratio, and strain rates were also calculated.

The approval of the University of Michigan Medical School Institutional Review Board (IRBMED) was obtained for the human studies described in this paper.

Results

The estimated duration of the second stage of labor and the numbers of voluntary pushes needed with respect to each pushing pattern are shown in Figure 3. The triple pushing method resulted in the shortest duration, 57.5 minutes ("triple" or Pre-Peak-Post pattern). The longest duration was 75.8 minutes ("pre-push" and "post-push" patterns). For the peak push technique, the duration of the second stage of labor increased by 16%. The increments of the duration of labor for the other pushing patterns, namely pre & peak pushing, peak & post push, pre-push and post-push, were 5%, 5%, 36% and 32%, respectively. However, the estimated numbers of the maternal pushes required to deliver the fetus for the triple push technique was 59, while the peak push technique only required 23 voluntary pushes, a 61% reduction. The reductions in the numbers of voluntary pushes for the pre-and-peak push, peak-and-post push, pre push and post push patterns were 29%, 30%, 54% and 56%, respectively.

To investigate the sensitivity of the duration of the labor to the magnitude of the voluntary push, the magnitude of the voluntary push was varied by 25%. With the triple push pattern, the duration of labor was found to be increased by 10% when the magnitude of the voluntary push was reduced by 25%. The duration of labor was reduced by 11% when the magnitude of the voluntary push was increased 25%. With the peak push pattern, the duration of labor increased 9% when the magnitude of the voluntary push was reduced 25%, whereas the duration of labor was reduced by 14% when the magnitude of voluntary push was increased by 25%. An example of the progress in a simulated vaginal delivery and the changes in muscle stretch ratios over time during the second stage of labor with peak push pattern is shown in Figure 4. The progress in the location of the fetal head between contractions was fairly uniform. However, the extra descent due to each voluntary push was small at the beginning of the second stage but increased rapidly prior to delivery. The estimated stretch ratio of the dorsal portion of the iliococcygeal muscle (IC6) was small during the whole second stage of labor and its maximal stretch ratio was a modest 1.32. The stretch ratio of the pubovisceral muscle band PV4 increased linearly through the second stage of labor and reached 1.59. The medial-most pubovisceral muscle band (PV2) exhibited the largest stretch ratio, 3.30, during the second stage of labor. The increment in the muscle stretch ratio was small at first but rose rapidly at the end of the second stage of labor. With the peak push pattern, the strain rate of the medial-most pubovisceral muscle band, PV2, reached 3.33 per second. The maximal strain rate of the PV2 muscle band for the different push patterns is shown in Table 2.

The maximal tensile stress in each muscle band during the delivery with the different pushing patterns was also estimated. The PV2 muscle band underwent the highest stress. The maximal stresses for the six push patterns are shown in Table 2.

Discussion

Although the “triple push” pattern resulted in a 16% shorter second stage, this came at the energetic expense of a 61% increase in the number of pushes required. These computer simulation results provide theoretical insights into how the maternal pushing pattern may affect the duration of the second stage of labor and the amount effort required to deliver the fetal head. The standard 3-push paradigm resulting in the shortest duration of labor, nine minutes shorter than the peak push pattern (i.e., spontaneous pushing), is consistent with clinical studies of self-directed, spontaneous, pushing that reveal a 5 to 13 minute longer second stage.(14) If one considers maternal “effort” as metabolically proportional to the summed area under the maternal expulsive force-time curve, the maternal bearing down effort required with the triple push was almost three times more than for the peak push pattern. This raises the possibility that some women who push three times during each contraction could become exhausted before achieving delivery.

Our birth simulation results also showed that the efficiency of a voluntary push in advancing the fetal head along the Curve of Carus is sensitive to the timing of that push. The fact that a voluntary push timed at peak uterine contraction was found to be the most efficient technique was due to the higher peak total push force, the higher peak tissue strain and the higher residual strain in the (viscoelastic) pelvic floor muscles between contractions. These results suggest that pushing at the wrong time is not only inefficient but also may waste maternal effort.

The endurance of striated muscle performing repetitive contractions is known to be inversely proportional to the muscle contraction level, the ratio of contraction time to cycle time (the duty cycle), and the cycle time, with the first two factors being the most important. (15) In labor the cycle time is essentially fixed by 3 minute uterine contraction interval, so if we assume that the muscle volitional contraction level is maximum, then minimizing the duty cycle is the obvious way to maximize endurance during delivery. In short this means minimizing the muscle contraction time needed to deliver the baby.

The ability to birth a baby without requiring an instrumented delivery is important because a prolonged second stage of labor that ends with an instrumented delivery has been associated with pelvic floor injury (see Introduction). It has been traditional in the United States to coach women to push three times, beginning at the onset of a uterine contraction, in order to shorten the duration of the second stage of labor. Whether alternative strategies result in less exhaustion and higher delivery rates will require clinical trials.

In terms of muscle injury risk *in vivo*, the magnitude of muscle stress in tension is a known predictor of striated muscle injury severity, and stretches greater than 50% strain are known to result in significant force deficits in passive muscle. (21) Increasing the strain rate can increase the risk of strain-related injuries in a passive muscle-tendon unit subjected to high rates of stretch.(22) During the simulated vaginal delivery, the medial-most pubovisceral muscle band (band ‘2’) underwent the largest stretch, experienced largest stress and highest strain rate in the final push of the delivery (Figure 3). Therefore this portion of muscle is at greatest risk of stretch-induced injury.(7) A practical way to reduce its risk of injury would be to reduce its rate of stretch by slowing the descent rate of the baby’s head during that final push.

In order to validate the present computer simulation results, the time histories of simulated maximum anterior-posterior (AP) vertex diameter from the model using the peak pushing pattern was compared with the measured increase in the AP vertex diameter measured *in vivo* in six primipara (Jane Walder, personal communication, Figure 5). Despite the large

variation in the AP diameter measurements, the overall trend of the simulation result was similar to the experimental measurements, helping to validate the model predictions.

This study has several methodological limitations. First, stretch is not necessarily uniform along a muscle band, as assumed. For example, localized stretch variation may occur along and across a muscle band,(23) especially if the thickness of the muscle varies.(24) Therefore, the assumption of the uniform tissue stretch led to a conservative estimate of tissue stresses and stretch ratios. Second, this analysis focused on the longitudinal stretch in the muscle bands; transverse compression and biaxial stretch effects were neglected. However, the overall trend predicted by this model should still be valid.

Third, as a first-order approximation, the fetus was represented by a rigid sphere in this simulation. The variations in fetal head shape, the degree of molding during delivery, the fetal head orientation, the size and shape of the fetal body, and pelvic shape may also affect the muscle stretch ratios and stresses. However, these effects are beyond the scope of this report. Fourth, in this model, the levator ani muscle bands were assumed to form a continuous U-shaped sling wrapped around the fetal head and birth canal. However, the pubovisceral muscles insert into the intersphincteric groove and perineal body. Therefore, the stretch of the anal sphincter and perineal body may affect the accuracy of the estimation of the pubovisceral muscle stresses and stretch ratios.

The effect of maternal fatigue was not simulated in this model. During the simulation, the magnitude of the voluntary push was assumed to be constant. However, muscle fatigue may develop gradually over time such that women can no longer maintain a given push force. As the result, the duration of labor may be underestimated. Finally, epidural anesthetic may influence pushing in two ways. First, the degree of abdominal muscle paralysis may decrease the pushing force, which would tend to lengthen the second stage, but it would also reduce the pelvic floor resistance to stretch, which might tend to shorten the duration of labor.

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Figure 1.

Panel A shows the initial geometry of the female pelvic floor at the beginning of the second stage of labor in a left lateral view; Panel B shows a left lateral view of the pelvic floor model; Panel C shows a left three-quarter view of the model; while a free body diagram of the model is shown in lateral view in Panel D. (© Biomechanics Research Laboratory, University of Michigan)

Figure 2.

Panels A–F illustrate the assumed time histories of the intrauterine pressure in the Triple, Peak, Pre and Peak, Peak and Post, Pre and Post pushing patterns, respectively. (© Biomechanics Research Laboratory, University of Michigan)

Figure 3.

The top panel shows the predicted effect of the six different push patterns on the duration of labor; while the bottom panel shows the estimated number of the voluntary pushes required for the different push patterns. (© Biomechanics Research Laboratory, University of Michigan)

Figure 4. Simulation results showing the progress of the vaginal delivery for the peak pushing pattern during the second stage of labor (Panel A) and the corresponding temporal changes in the

muscle stretch ratios (Panel B). The labels '2', '4' and '6' denote the muscle band under consideration. Panel C shows the assumed time history of the intrauterine pressure during the second stage of labor. Panel D shows an expanded graph of the time history of the stretch ratio circled in Panel B. (© Biomechanics Research Laboratory, University of Michigan)

Figure 5.

The changes in maximum AP vertex diameter measured at the peak maternal push in seven primiparas are shown by the solid lines. The dashed line shows the change in estimated AP diameter of the model hiatus at the peak push pressure for the peak push pattern. (© Biomechanics Research Laboratory, University of Michigan)

Table 1

The values of material property parameters used in this study are shown.

	E0	E1	E2	$\mu 1$	$\mu 2$
Muscle	3.1×10^5 Pa	1.4×10^6 Pa	1.0×10^4 Pa	4.5×10^6 Ns/m ²	7.1×10^7 Ns/m ²
	A			B	
Ligament	2.6×10^5 Pa			11.85	

Table 2

The maximal strain rate of PV2 muscle and the maximal stress within levator ani muscle bands are shown in the Table.

	Maximal Strain Rate (s^{-1})	Maximal Stress (Pa)
Triple Push	3.42	5.45×10^6
Peak Push	3.33	5.44×10^6
Pre & Peak Push	3.32	5.43×10^6
Peak & Post Push	3.31	5.45×10^6
Pre Push	2.48	4.89×10^6
Post Push	2.47	4.94×10^6