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Forces Involved with Labor and Delivery—A Biomechanical Perspective

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Abstract—Childbirth is a primarily biomechanical process of physiology, and one that engineers have recently begun to address in a broader fashion. Computational models are being developed to address the biomechanical effects of parturition on both maternal and fetal tissues. Experimental research is being conducted to understand how maternal tissues adapt to intrauterine forces near the onset of labor. All of this research requires an understanding of the forces that are developed through maternal efforts—both uterine contractions and semi-voluntary pushing—and that can be applied by the clinician to assist with the delivery. This work reviews the current state of knowledge regarding forces of labor and delivery, with a focus on macro-level biomechanics.

Keywords—Birth, Biomechanics.

INTRODUCTION

A number of physiological processes can be evaluated from a primarily biomechanical standpoint—including circulation of blood through the cardiovascular system and movement achieved through the musculoskeletal system. Both of these organ systems have long been the focus of biomechanical engineers—with significant experimental and modeling work that has advanced our understanding of these processes from the macroscale to include cellular biomechanics and mechanobiology. Parturition—childbirth—is also a predominantly biomechanical process, but one that has not received the same level of attention. In the past two decades, increasing attention has been paid to both the effect of childbirth on maternal and fetal tissues, as well as the effect of changes in maternal tissue properties on the initiation of labor. However, there are still key, foundational questions that must be answered about such a fundamental physiological process. Perhaps the first building block needed for a complete understanding of the biomechanics of childbirth are the forces that are produced during labor and delivery. Such knowledge will first serve as a fundamental component of understanding the physiological and pathophysiological processes of parturition. Of even greater interest to engineers, perhaps, is the importance of this foundational information for the development of models of the effects of normal and abnormal childbirth on both maternal and fetal outcomes. This review will assess the current state of knowledge related to the forces that are important in labor and delivery and will identify key questions that deserve attention as we advance research in maternal reproductive biomechanics.

The focus of this review is primarily on macro-level biomechanics, with a brief look at changes in myometrial biomechanics due to systemic pathologies. For those individuals interested in an introduction to the tissue-level physiology and biomechanics, Garfield and colleagues published a broad review in 1998 that discusses fundamental changes in uterine physiology during pregnancy and parturition.[29]

CHILDBIRTH—A PRIMER FOR ENGINEERS

Parturition involves the movement of the fetus from the protective environment of the uterus, through the maternal pelvis and birth canal, and out to the wider world. In order to allow for the distension that occurs

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during the birth process, the soft tissues of the vagina and perineum remodel during pregnancy—becoming more vascular and demonstrating a reduction in stiffness of the connective tissue.[24] This remodeling is a complex process that involves a combination of hormonal[46] and mechanical signaling.[28]

Once labor is triggered—either at term or prematurely—uterine contractions act to dilate the cervix and advance the infant through the maternal pelvis. The *first stage* of labor is defined as the period from labor onset (establishment of regular contractions) through complete dilation of the cervix (10 cm dilation and full effacement/thinning). The first stage of labor is further divided into latent and active phases, with the start of the active phase defined based on the establishment of a regular contraction pattern that dilates the cervix to between 3 and 6 cm.[24] The *second stage* of labor extends from complete cervical dilation through to delivery of the infant, and it normally involves semi-voluntary maternal pushing in conjunction with contractions. The *third stage* of labor involves delivery of the placenta.

In modern times, the vast majority of vaginal births occur with the infant in a cephalic (headfirst) presentation. Breech presentations, with either the feet or buttocks as the presenting part, will often be delivered by cesarean section. For a cephalic delivery, the infant will advance through the pelvis with the *station* defined based on the location of the top of the infant's head in comparison with the ischial spines of the mother's pelvis (Fig. 1). It is typically scored between − 3 and + 3, or − 5 and + 5, with a score of 0 indicating that the head is at the level of the ischial spines. Negative numbers represent the head being above the level of the ischial spines, while positive numbers represent the head being further down towards the pelvic outlet.

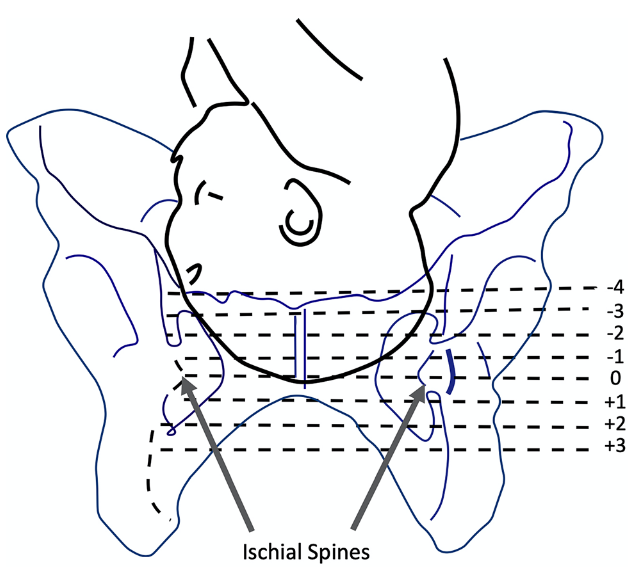

FIGURE 1. Schematic illustration of fetal station, which is measured based on the distance of the presenting part of the infant (typically the head) above or below the ischial spines.

As the infant moves into the pelvis and the birth canal during the first and second stage of labor, it undergoes seven cardinal movements of labor[39] (Fig. 2). It should be noted that these movements are purely passive in nature, as the infant's body interacts with the maternal pelvis and soft tissues. *Engagement* occurs when the largest diameter of the infant's head enters the maternal pelvis. This may actually occur before the onset of labor. *Descent* involves the continued movement of the head through the pelvis. During descent, the infant will undergo *flexion*, where the chin is tucked in towards the chest to facilitate progression of the head through the pelvis. This is followed by *internal rotation*, where in most cases the infant's head is rotated to an occiput anterior presentation—with the face pointing down towards the mother's spine. After the head has rotated, the infant's neck extends, and the chin moves away from the chest as the head follows the shape of the maternal pelvis to rotate under and around the symphysis pubis—this is termed *extension*. As the infant's head delivers, it then rotates so that it is in a neutral alignment with the shoulders, which will typically be in a slight angle from an anteroposterior (up/down) orientation. This is known as *external rotation* or *restitution*. Finally, *expulsion* results in the complete delivery of the infant's body—with the anterior shoulder delivering first, before the posterior shoulder and then the torso.

In addition to the movement of the infant's body as it transitions through the pelvis, the infant's body itself can experience deformation due to the pressure produced both within the uterus and by the tissues of the birth canal. The primary example of this is molding of the fetal head during labor. Because the sutures of the fetal skull have not fused at the time of birth, the skull is able to respond to the forces through an overlapping of the cranial bones. This effectively reduces the diameter of the skull, allowing it to fit through the openings of the bony pelvis.[44]

While childbirth is considered by many to be a simple and automatic process, rates of complication due to biomechanical factors are still significant. A failure to progress in labor due to ineffective uterine contractions and/or maternal pushing efforts may result in an instrumented delivery (e.g. use of vacuum or forceps) or a decision to convert to a cesarean section. Cephalopelvic disproportion—a mismatch between the size of the maternal pelvis and the infant's head that prevents the passage of the fetus through the pelvis—is estimated to occur in between 1 and 8% of deliveries worldwide and generally requires a cesarean section to avoid both maternal and fetal death.[52]

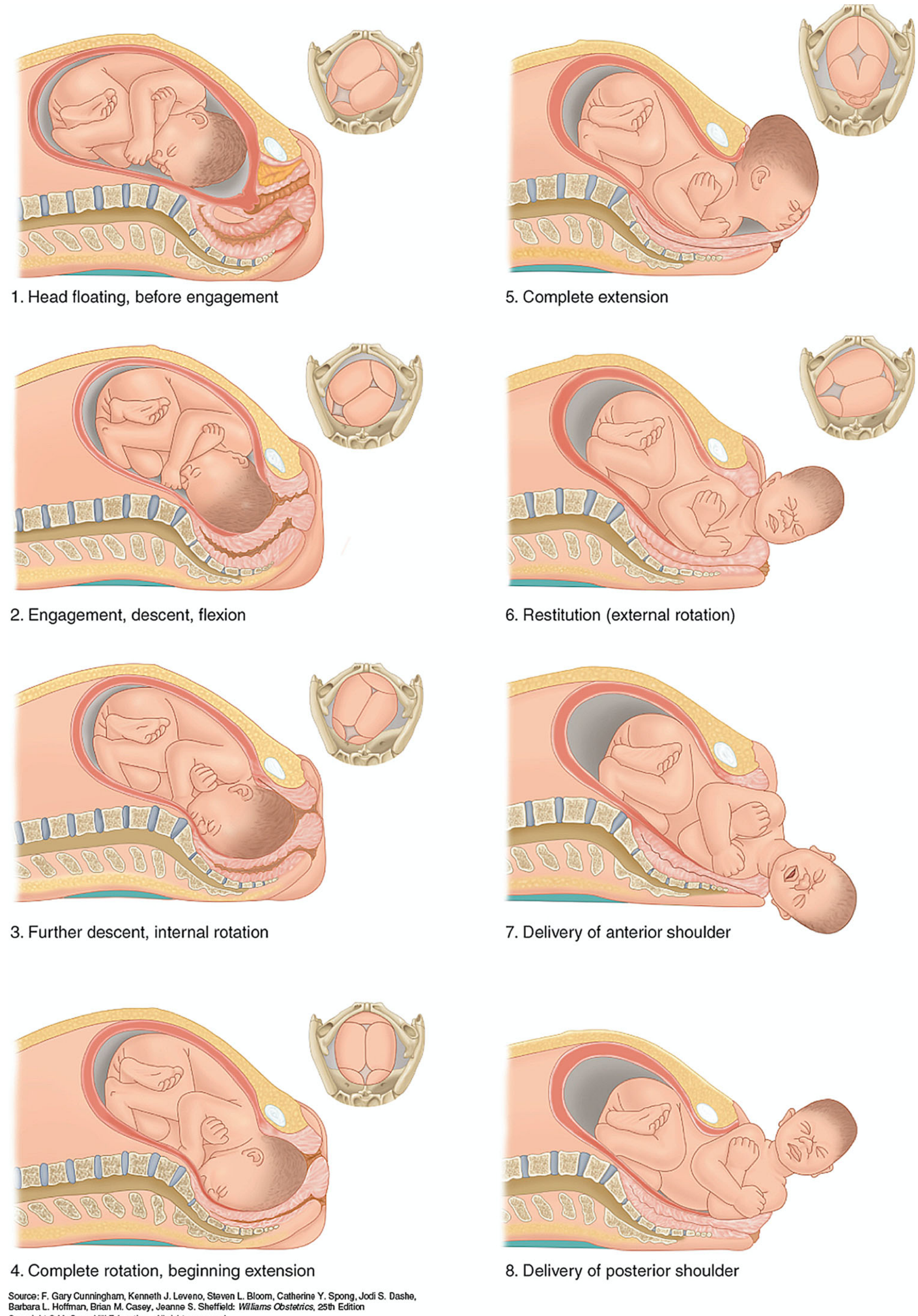

FIGURE 2. Cardinal movements of labor from a Left Occiput Anterior position (i.e. back of infant's head facing mother's left leg). Reprinted with permission from McGraw Hill Education, as originally published in *Williams Obstetrics.*[24]

Shoulder dystocia—a delay in delivering the infant's shoulders after the delivery of the head—occurs when one of the infant's shoulders impacts with the mother's symphysis pubis.[31] Shoulder dystocias are documented in about 1% of deliveries[31] and can occur independent of the size of the infant, typically based on a failure of the infant's shoulders to rotate from a true antero-posterior orientation to a slightly oblique presentation.

Throughout the phases of parturition, the forces produced by the mother—typically referred to as maternal forces or endogenous forces—are a key factor in both the dilation of the cervix and the advancement of the fetus through the pelvis. Understanding how those forces are produced and transmitted to the fetus—both in terms of magnitude and direction—is imperative for a biomechanical analysis of labor and delivery.

THE PURPOSE OF UTERINE PRESSURE AND FORCES IN CHILDBIRTH

Other than the simplified assertion that uterine contractions are designed to deliver the fetus from the maternal to the external environment, what is the physiological role of the generated forces? Labor is not a uniform phenomenon—with uterine activity changing between latent and active labor, as well as between the first and second stages of labor.

During the first stage of labor, a key function of the forces generated by the uterus is to dilate the cervix. Allman and colleagues hypothesized that the connection between those two physiological phenomena was two-fold.[4] First, that the uterine contraction generates a direct force through the infant's body to the head and onto the cervix, similar to a piston. Second, that the contraction of the uterine muscles acts to pull the cervix upwards past the head—like ''pulling on socks.'' The process by which the temporal variation of a uterine contraction pulls on the cervix to dilate it and move it up past the fetal head is clearly described by Caldeyro-Barcia *et al.*[19] Further evidence of these two contributions to cervical dilation can be found in the work of Luria and coauthors, who measured fetal station (position of the infant's head within the maternal pelvis) and cervical dilation simultaneously and continuously. When plotting time matched fetal station against cervical dilation during a contraction, two directions of curve were identified. Clockwise rotation indicated that the fetal head descended further into the pelvis before the cervix opening increased—an illustration of the piston effect. Counterclockwise rotation in the curves indicated that the cervix dilation occurred before the head moved down within the pelvis, indicating that the soft tissue is being pulled up past the infant's head. As had been found with earlier indirect measures of the head-to-cervix contact force,[12,45] Allman *et al.* found a positive relationship between the magnitude of the force and the rate of cervical dilation. Thus, rather than supporting the hypothesis that higher head-to-cervix force represents a negative indicator for a successful labor through the concept of increased cervical resistance, increased force should be viewed as a positive indicator of a key mechanism through which cervical dilation occurs.[4] With higher head-to-cervix forces, a labor is more likely to progress to a successful vaginal delivery rather than be converted to cesarean section.[34]

One application of evaluating uterine contraction forces can be to estimate the distension force (tension) that is acting to dilate the cervix. With this goal in mind, Manabe and Sagawe developed an elegant mathematical assessment that relates the tension in the cervix to the resultant force produced through uterine contractions.[47] While the derivation does not include any experimental data, the paper provides a unique, quantitative analysis of the relationship between the cause and effect of traction on the cervix. They later applied their model to estimate the change in the force of cervical dilation before and after membrane rupture.[48]

As the fetus descends into and through the pelvis in both the first and second stages of labor, it is the coordinated contraction of the uterus—and the addition of increased abdominal pressure from the direction of the fundus during pushing—that advances the presenting part of the infant (typically the head). The round ligaments (Fig. 3) are musculotendinous structures that act to keep the uterus in an appropriate orientation during pregnancy.[20] Active contraction and passive tension within the round ligaments during uterine contractions prevent the fundus from being elevated and therefore contribute to the advancement of the fetus down into the pelvis.[19]

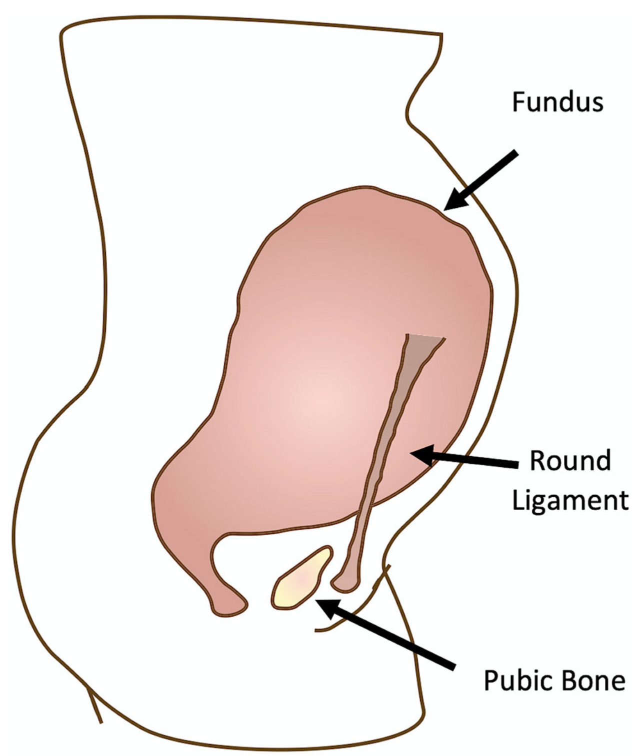

FIGURE 3. Basic anatomy of the gravid uterus, showing the fundus and the round ligament in relation to the maternal abdomen and pubic bone.

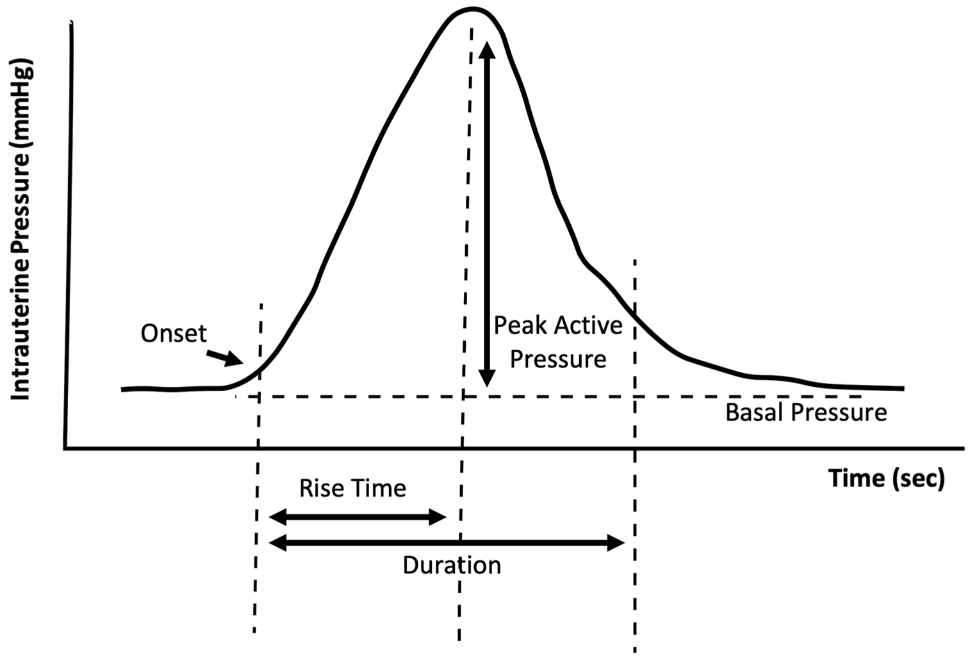

FIGURE 4. Characteristic properties of a uterine contraction waveform, as defined by Steer.[61]

In the complex biomechanical phenomena that comprise labor, there are many factors that can play a role in the variations that are seen. Steer's research group determined that any unified biomechanical theory of labor must account for variations in both input parameters (e.g. parity, administration of induction or augmentation agents, infant size) and output parameters (e.g. speed of labor).[4] For example, in a mother who has previously delivered a large number of infants (i.e. grand multiparae, P5 and higher), the increased compliance of the cervix means that less uterine activity during the 1st stage of labor will still dilate the cervix at an adequate rate.[7] At the macro and tissue-level, there is still a substantial opportunity to develop such a unified model. While some electro-mechanical, chemo-mechanical, and electro-chemo-mechanical models of uterine contraction have recently been developed,[59,66–68] such models are in their infancy. Currently, they all look at force generation and expulsion of the fetus from the isolated uterus, without including any of the resistive tissues of the pelvis or the pelvic floor musculature. In addition, they have not yet integrated any of the anatomical, physiological, or pharmacological variations that Steer has called for in a unified biomechanical model of labor. With advances in mechanobiology as well as computational modeling, this area of research is wide open for further inquiry to answer key remaining questions.

CONTRACTION PATTERNS OF THE UTERUS

The contraction wave form is generally shaped like a bell-shaped curve (Fig. 4). There are three important temporal components of a uterine contraction from a biomechanics perspective—the frequency of the contractions, the duration of each contraction, and the rate of increase (and decrease) in the myometrial contraction. Steer measured the duration of a contraction as the time between the abrupt rise in pressure from baseline relaxation to an offset pressure, typically about 5 mmHg above baseline.[62] Typical contraction patterns during the active portion of the first stage of labor involve frequencies of 2 to 5 contractions per 10-min period,[19] or 23 contractions per hour.[44] During this phase, an average duration of a contraction is about 60 s.[62] The rise time of a contraction has been measured clinically to be about 25 seconds during the active first stage of labor,[62] with only a short period of time at the peak pressure before relaxation begins over the same type of time frame. Caldeyro-Barcia *et al.* reported that the rise time was typically between 30 and 60 s,[19] with the longer time corresponding to periods of less frequent contraction. He also stated that the relaxation phase takes longer than the contraction phase.

In 1976, Donati *et al.* identified 25 parameters to fully describe a waveform from a standard intrauterine pressure catheter tracing.[25] The parameters were determined so as to characterize both the temporal and pressure components of the curve, including both the increasing and decreasing pressure patterns. While the research team realized that the characteristics were too complex to be implemented for clinical analysis, such detailed analysis of the variations in intrauterine pressure may be useful when attempting to develop an engineering model of labor and delivery.

The force generated by the uterus is not evenly distributed through the structure at each instant in time. Caldeyro-Barcia *et al.* believed that, for normal labor, the contraction wave is initiated at the fundus and then progresses down through the midzone to the lower segment and the cervix with a slight time shift.[19] They measured tension within the myometrium using microballoons implanted within four locations of the uterine wall, each connected to a manometer. While the contraction in the various locations was seen to start at slightly different times, the peak force was found to occur almost simultaneously in all regions and then relax synchronously. They documented that the initiation of the contractile wave takes about 10 to 20 s to move through the uterus. In addition, as the myometrium is thicker towards the fundus and thinner towards the lower segment of the uterus, the intensity of the contraction is stronger in the upper portion of the uterus. The combination of these phenomena (downward propagation of the wave, decrease in wave duration from fundus to cervix, and decreasing intensity of contraction from fundus to cervix) were termed the "Triple Descending Gradient", and the presence of these characteristics was felt to be key to both cervical dilation and fetal descent (see "The Purpose of Uterine Forces and Pressure," above). Inversions to any or all of the components of the Triple Descending Gradient can and do occur, each of which can result in a failure or delay in the progression of labor[19] but may not be readily detectable through traditional tocometer or intrauterine pressure catheter (IUPC) measurements.

Building on the work of Caldeyro-Barcia from the 1950s, the coordination of contraction and response in the uterus was further investigated by Allman and colleagues in the mid-1990's. By comparing the temporal response of the intrauterine pressure measured towards the fundus with the resistive force generated between the fetus' head and the maternal cervix, it was possible to determine how those two quantities were connected.[5] Three different patterns of force-pressure relationships were identified. A positive loop (Fig. 5a) demonstrated that intrauterine pressure increased first, followed by the head-to-cervix contact force. A neutral loop (Fig. 5b) showed a temporal alignment of pressure and resistive force, as they increased and decreased simultaneously (less than a 2 s offset). Finally, a negative loop (Fig. 5c) showed an increase in the force between the head and cervix before the pressure increased in the amniotic fluid near the fundus. Patients were grouped based on whether they were undergoing a normal progression of labor with spontaneous onset, a slow progression of labor following spontaneous onset, or an induction of labor. The three patterns of contraction were seen in all patients, and there was no significant differences between the groups. However, there was a significantly higher percentage of negative loops for both spontaneous or induced labors where oxytocin was used (for either induction or augmentation)—though there was substantial overlap between the groups (oxytocin vs. no oxytocin). Of note, in those deliveries where measurements could be made both before and after the administration of oxytocin, there was a trend (though not significant) towards an increase in the percentage of positive loops and a decrease in the percentage of negative loops after administration of the drug. In all

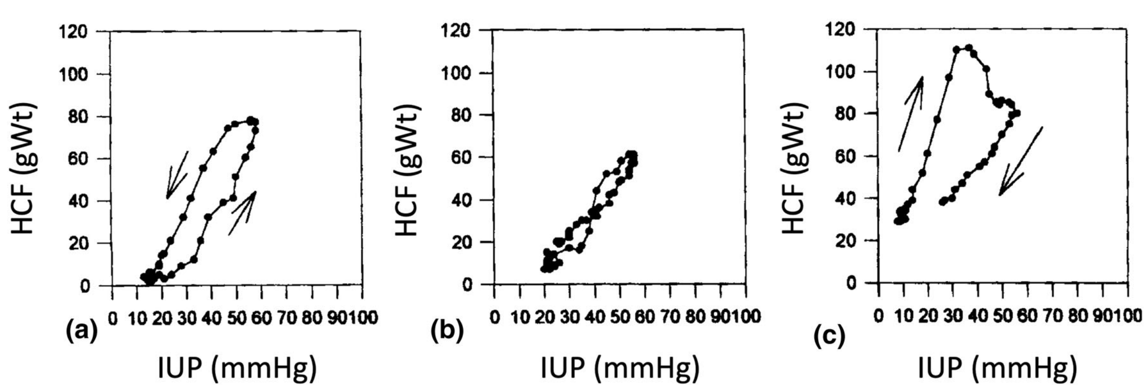

FIGURE 5. Examples of the three possible temporal relations between intrauterine pressure (IUP) and head-to-cervix contact force (HCF). (a) shows a positive loop, where IUP increases before HCF. (b) shows a neutral loop, where IUP and HCF rise simultaneously. (c) shows a negative loop, where IUP lags increases in HCF. Reproduced with permission from John Wiley and Sons and originally published by Allman et al.[5]

labors, the percentage of positive loops tended to increase with increasing frequency of contractions, with the percentage of negative loops concurrently decreasing at higher frequencies of contractions. Both relationships were statistically significant, but with R values of 0.36 and -0.34, respectively. However, there was no relationship between the distribution of the types of loops and the state of cervical dilation (i.e. < 4, 4–7, or 7–10 cm). Allman *et al*. hypothesized that the predominance of the negative loops was the result of a need to create a seal between the fetal head and the cervix before the intrauterine pressure could increase as the uterus contracted. Thus, a positive loop only occurs if the head remains in contact with the cervix between contractions. This aligns with the relationship between contraction frequency and the percentage of positive loops—less time between contractions provides less opportunity for the head to shift away from the cervix slightly. For models that intend to investigate the dilation of the cervix during labor, including this variation in apposition of the fetal head and the cervix—and the resulting change in relationship between increasing intrauterine pressure and head-to-cervix pressure—may be a key phenomenon in the various possible outcomes (e.g. successful labor or prolonged first stage).

The cellular mechanism of coordination of uterine contractions is still a matter of scientific debate. Pacemaker regions,[43] "automata" with self-sustaining contraction patterns that influence neighboring cells,[11,69,71] myocytes that act as independent oscillators that become increasingly coupled,[61] the presence of "Cajal-like" interstitial cells within the myometrium,[38] and more diffuse mechanotransduction responding to increased intrauterine pressure[42,70] have all been recently proposed. This is an area that is ripe for continued investigation, as controlling this coordinated contractile activity may be the key to both supporting effective labor and intervening in cases of pre-term labor.

MEASUREMENTS OF INTRAUTERINE PRESSURE—FIRST STAGE OF LABOR

During clinical deliveries, intrauterine pressure is commonly measured in Montevideo units through an intrauterine pressure catheter (IUPC). Montevideo units are calculated as the sum of the peak pressure (in mmHg) of the contractions that take place over a 10-minute period of time.[30] However, the IUPCs used do not undergo the calibration that is expected for an engineering assessment of pressure, and they are susceptible to error if tissue partially or fully obstructs the catheter tip.[13] Thus, while IUPC monitoring provides important clinical information, from an engineering point-of-view the information that they convey is more of a semi-quantitative indication of the pressure generated by the uterus during labor.

In 1984, Smith published a review of the history of measurements of intrauterine pressure, which had been attempted starting in 1872.[60] The technology available from the 19th to the mid-20th century, which typically involved a balloon attached to a manometer via tubing, limited the accuracy of these measurements—but provided some important information regarding uterine activity. Lindgren[44] presented what remains today the most complete analysis of intrauterine pressure during various stages of labor. A small number of additional studies have been conducted in the past 30 years using fully calibrated pressure sensors during clinical deliveries. A fraction of these have actually reported on the range of values measured for intrauterine pressure. These studies give us a good understanding of the normal range of pressures developed by the uterus. These values are summarized in Table 1.

The majority of measurements of intrauterine pressure have been made after membranes have ruptured—as most pressure transducers require the presence of fluid to interact with the transducer's membrane. Ingelman-Sundberg and Lindgren created a probe that included both encapsulated strain gauges, to mimic a membrane transducer, and exposed spring-based strain gauges.[40] They found that the encapsulated transducers were not able to register a quantitatively realistic pressure between the fetal membranes and the uterine wall before the membranes ruptured, and they attributed this to the fact that there was only a small amount of air—and no amniotic or other fluid—between the myometrium and the fetal membranes at that time. After membranes were ruptured, the encapsulated gauge within the corpus of the uterus was able to measure the pressure quantitatively; however, when the gauge was positioned in the lower uterine segment—where there is minimal amniotic fluid—it was not able to register a pressure. With the spring-based strain gauges, it was possible to measure intrauterine pressure prior to membrane rupture based on the contact with the tissues; however, the accuracy of the pressure measurement depended on the orientation of the gauge. When the spring receptor was positioned to face the fetal membranes, the curve matched a concurrently measured amniotic fluid pressure within the membranes. However, when the spring receptor was facing the uterine wall, it had a much lower magnitude than the actual pressure curve. That difference was no longer evident after the membranes had ruptured, based on the presence of amniotic fluid around the receptor. The key conclusion from this set of experiments is that intrauterine pressure measurements generally require the presence of

TABLE 1. Range of experimentally measured intrauterine pressure during 1st stage of labor. Data are listed as mean ± SD where available. Ranges are provided in parentheses.

Research group	Number of patients	Patient characteristics	Measurement characteristics	Peak uterine pressure (mmHg)	Basal tone pressure (mmHg)
Lindgren[42]	4	Normal Labor—Primigravid	Mean maximum pressure over 60 min (cervix 3–6 cm)	34.4 ± 0.08	8.9 ± 0.3
	5		Mean maximum pressure (cervix 8-10 cm)	41.7 ± 2.4	9.3 ± 0.8
	8	Normal Labor—Multigravid	Mean maximum pressure over 60 min (cervix 3–6 cm)	49.3 ± 1.3	8.7 ± 0.3
	5		Mean maximum pressure (cervix 8–10 cm)	68.9 ± 4.1	10.5 ± 1.0
Steer[61]	20	Induced	Mean of patients at various time points during 1st stage	24 ± 10 to 41 ± 13	Adjusted for in calculations of peak uterine pressure
Steer[5]	40	Varied	Mean over 1st stage of labor	10–60	
Olah[49]	63	Spontaneous Labor + Augmentation	Mean—latent phase of 1st stage	53–71	Not reported
		Induced	Mean—latent phase of 1st stage	41–62	

amniotic fluid around the transducer, which occurs after the membranes rupture. For pressure values before membranes rupture, customized transducers can be constructed—but they must be used cautiously to obtain realistic measurements.

In general, peak uterine pressure during the first stage of labor ranges from 10 to 50 mmHg, but can be as high as 60 to 70 mmHg. Lindgren found that during the first stage of labor, intrauterine pressure tended to be higher for multiparous women than for primiparous women, and that pressure in both groups increased after the membranes had ruptured.[44] He also found that pressure increased towards the end of the 1st stage of labor (8–10 cm dilation) compared to earlier in the stage (3–6 cm dilation). There is also some variation apparent based on whether labor initiated spontaneously or through induction.[51] In addition, for induced labors, the pressure builds from the initiation of labor to a stable phase.[62] While Steer's research group specifically described calculating the peak amniotic pressure as the value above the basal pressure (the inate pressure of the intrauterine environment),[4,62] the papers by Lindgren and Olah were not clear in how they determined the peak pressure. Basal pressures are typically around 10-15 mmHg[44,62] or possibly up to 20 mmHg.[57] To determine the effect of contractions on intrauterine pressure, subtracting the basal pressure from the measured pressure is appropriate.

ESTIMATES OF UTERINE FORCE—FIRST STAGE OF LABOR

It is not possible to measure either the tension generated by the myometrium or the resultant generated uterine force directly during a delivery. Therefore, either surrogates for uterine force or calculations for that parameter must be used.

Head-to-cervix force might be one experimentally measurable surrogate for overall uterine force during the first stage of labor. It can be seen as representing the resistant force generated by cervical tissue against the outward force from uterine pressure and myometrial tension. Gough *et al.*[34] developed a force transducer system to measure the contact force between the infant's head and the cervix over the course of the first stage of labor. They first applied this system in 31 deliveries, involving both multiparous and nulliparous women. The maximum value for the head-to-cervix contact force varied between contractions within individual patients, and also varied substantially between patients. The 50th percentile contact force calculated for each patient who went on to a vaginal delivery varied between about 22 and 100 g-wt (0.216 and 0.981 N).[34] However, in order to determine the overall resistive force, it is necessary to determine not just the force at one contact point between the cervix and the fetal head, but the sum of all of those point contact forces. The importance of this can be seen from the way in which the head-to-cervix sensor system was constructed with multiple force transducers[8] (Fig. 6). As the contact area will vary throughout the first stage of labor, while the cervix dilates, and the force at different points is not equal even within a single contraction,[34] this calculation could be extremely challenging—and has not yet been attempted within published literature. Thus, in terms of serving as a surrogate for uterine force, head-to-cervix contact force can best be used to indicate the wide variation in the uterine force produced—even within normal deliveries.

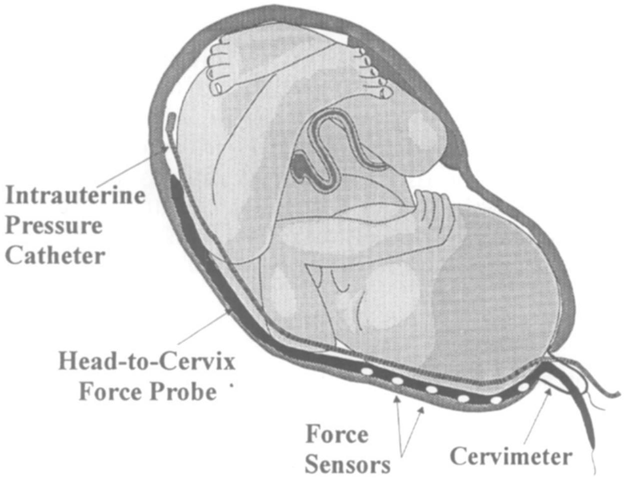

FIGURE 6. Sensor system developed by Antonucci et al.[8] to measure the contact force at multiple locations between the fetal head and the birth canal simultaneously. The presence of concurrent force measurements at each of the six sensors, which vary in magnitude and comparative amount during labor, demonstrates the importance of accounting for the total resistive force from the maternal soft tissues if this will be used as a way to estimate maternal expulsive forces. Reproduced with permission from Elsevier.

Prior to the work of Gough and Steer,[34] measurements of the contact between the fetal head and birth canal involved using pressure transducers rather than force transducers.[37,41,44,57] Gough raised the concern that the use of pressure transducers, which respond to hydrostatic pressure due to the surrounding fluid as well as pressures due to perpendicular forces, were not able to isolate the actual contact force between the head and the maternal tissue and were influenced by the amniotic pressure as well. In fact, these studies generally found that the measured contact pressures between the fetal head and the maternal tissues were 2–3 times higher than the concurrently measured intrauterine forces. Thus, even with the above discussed challenge of translating a point value to a resultant resistant force, the use of contact values from pressure transducers further clouds the assessment.

Steinman, in 1991, published a purely mathematical model relating the expulsive force as a function of intrauterine pressure and the unresisted area of the fetal head—defined based on the amount of dilation of the cervix.[63] He was attempting to explain the increase in the rate of cervical dilation that is seen clinically as the first stage of labor advances in normal labors. The model predicts that the magnitude of the force driving dilation will increase as labor continues, even if the peak intrauterine pressure remains constant. Unfortunately, while he indicated that his predicted pattern of dilation matched that of Gough,[34] the only validation provided was that it was the contact force (vs. contact pressure) that was the key factor driving dilation. No quantitative or semi-quantitative validation was provided, however, to advance this past a theoretical exercise.

MEASUREMENTS OF INTRAUTERINE PRESSURE—SECOND STAGE OF LABOR

While intrauterine pressure and the resultant force in the first stage of labor is due only to uterine contractions, in the second stage there is a significant added force that is provided by maternal pushing through the Valsalva maneuver. Such an action, which is only semi-voluntary,[14] increases the intrabdominal pressure—which is then transmitted to the uterine environment. Measurements of intrauterine pressure during the second stage of labor face the same challenges during clinical deliveries as during the first stage. There have been a small number of researchers who have made use of research protocols to accurately assess this parameter in the clinical realm. These data are summarized in Table 2.

As with measurements made during the first stage of labor, Lindgren[44] provides the most complete analysis of intrauterine pressure for various portions of the second stage of labor. For five primiparous women and five multiparous women, intrauterine pressure was measured throughout the second stage of labor, and he divided his measurements into two phases. The first was from the onset of the second stage through to the point where the head reached the pelvic floor, defined by him as descent. The second phase then represented the end of the 2nd stage of labor, extending from the time when the head reached the pelvic floor until delivery of the fetus. He recorded basal pressure of around 10 mmHg for both groups of patients and throughout labor. While multiparous women had a higher pressure due to contractions alone, as had been the case during the 1st stage of labor, during the final portion of the 2nd stage—to deliver the infant's head—primiparous women were noted to produce a greater pressure than multiparous women (means of 120.9 vs. 113.8 mmHg, respectively). This may be due to the fact that perineal and pelvic tissues have been found to become more compliant following a first vaginal delivery,[27] and primariparous mothers possibly were able—or required—to generate the higher pressure in order to overcome the increased resistance of the pelvic tissues.

Rempen and Kraus[57] measured intra-amniotic pressure along with head compression pressure in 42 spontaneous vaginal deliveries. They did not separate the women based on maternal characteristics. Data was reported for peak pressure within the amniotic fluid both as an average of the contractions during the

TABLE 2. Range of experimentally measured intrauterine pressure during 2nd stage of labor. Data are listed as mean ± SD, when available. Ranges are provided in parentheses.

Research group	Number of patients	Patient characteristics	Measurement characteristics	Peak uterine pressure (mmHg)	Basal tone pressure (mmHg)
Buhimschi[16]	52	Varied	Contractions Mean of 2nd stage	65.1 ± 2.0	20.5 ± 0.9
			Contractions with Valsalva Mean of 2nd stage	92.8 ± 2.2	23.3 ± 1.1
Buhimschi[17]	22	Varied	Contraction with Valsalva Mean from head at 3+	103 (88–118)	Not reported
			Contraction with Valsalva in McRoberts' Position—mean from head at 3+	129 (114–144)	
Rempen[55]	42	Varied	Contractions with Valsalva Mean of 2nd stage	141.6 ± 32.2	19.5
			Last contraction with Valsalva	151.3 ± 38.2	20.5
Lindgren[43]	5	Primigravid	Contractions alone Mean—descent of fetus	50.0 ± 1.7	9.7 ± 0.06
			Contractions alone Mean—end of 2nd stage	54.4 ± 1.4	10.3 ± 2.7
			Contractions with Valsalva Mean—descent of fetus	107.8 ± 5.2	9.7 ± 0.06
			Contractions with Valsalva Mean—end of 2nd stage	120.9 ± 3.4	10.3 ± 2.78
	5	Multigravid	Contractions alone Mean—descent of fetus	65.0 ± 2.4	10.8 ± 1.1
			Contractions alone Mean—end of 2nd stage	68.6 ± 2.7	10.9 ± 1.0
			Contractions with Valsalva—descent of fetus	110.9 ± 5.3	10.8 ± 1.1
			Contractions with Valsalva—end of 2nd stage	113.8 ± 3.6	10.9 ± 1.0

second stage and for the last contraction. The average peak pressure among the 42 subjects increased from 141.6 to 151.3 mmHg when comparing the majority of the pushing phase to the final contraction, at which point the head was delivered. This was similar to the finding of Lindgren[44] that pressure was higher at the very end of the second stage of labor. The measured basal pressure in the amniotic fluid was about 20 mmHg and did not change significantly between the second stage as a whole and the last contraction.

Buhimschi and colleagues measured intrauterine pressure in 52 women of a range of maternal characteristics[16] during the second stage of labor. Pushing was not started until the head was at + 2 station (− 3 to + 3 scale), and pressure with contractions alone was measured for 15–20 min before pushing started. The average reported maximum amplitudes were 65 mmHg during contractions alone and 99.6 mmHg for contractions with Valsalva. The data were not clear in whether the reported maximum amplitude was determined directly from the "raw data" or was the difference between basal (20.5–23.3 mmHg) and peak values for intrauterine pressure. In either case, the measured pressure values with Valsalva are significantly lower than those reported by other researchers.

Buhimschi's research team also assessed how the use of McRoberts' maneuver (hyperflexing the maternal thighs against the abdomen,[32] typically used in cases of shoulder dystocia) affected the generation of intrauterine pressure compared to pushing alone and pushing with a contraction.[17] Most of the reported data was based on the integral of the pressure-time curve (mmHg s), which makes it more difficult to compare to other reported data. However, they did say that the mean pressure amplitude increased from 103 mmHg with Valsalva and contractions in stirrups to 129 mmHg if the mother was pushing with contractions while in McRoberts' position. Thus, placing a mother in McRoberts' position can improve the efficiency of pushing. However, having the mother simply push to clear a shoulder dystocia is currently contraindicated, as it will both worsen the impact and stretch the brachial plexus.[33] Unfortunately, Buhimschi did not report on whether intrauterine pressure increased simply by placing the mother in McRoberts' position in the absence of any spontaneous or voluntary efforts to generate a maternal force.[17] Therefore, it is not possible to conclude whether the use of McRoberts itself may generate intrauterine pressure, whether it is detrimental or beneficial.

Similar to most of the data reported for the first stage of labor, those researchers that reported both peak intrauterine pressure and basal tone pressure did not clearly describe whether they had already accounted for basal pressure in their maximum pressure data. This makes it a greater challenge to determine what values of intrauterine pressure to use for models of labor or calculation of forces. However, some general trends can be determined: (1) intrauterine pressure varies during the second stage of labor, increasing towards the very end; (2) maternal pushing (Valsalva maneuver) substantially increses intrauterine pressure compared to contractions alone; and (3) pressures of 115 mmHg in multiparous women and 120 mmHg in primiparous women are normal.

ESTIMATES OF INTRAUTERINE FORCE—SECOND STAGE OF LABOR

In 1954, Matz provided a review on the subject of ''uterodynamics and labor''.[49] In addition to discussing the current state of knowledge regarding uterine physiology, he provided values for the force provided by the uterus. In his estimation, but without reference or calculation, he stated that the force necessary to move a baby through an average pelvis was 95 lbf (422 N), while the force that could be provided by the uterus was 54 lbf (240 N). Thus, by Matz's estimation, the remaining 41 lbf (182 N) needed to be provided by either maternal pushing or the application of forceps (this was before vacuum assisted delivery was available). He went on to indicate that the resistance force of the pelvic musculature averages 30 lbf (133 N), such that arithmetically the soft tissues of the birth canal must provide an additional 11 lbf (49 N) of resistance. Interestingly, he used these estimates to justify routine episiotomy, regional anesthesia to relax pelvic tissues, and the proficient use of forceps in order to reduce the forces that the fetus would need to experience and tolerate during childbirth. While neither the analysis nor the resulting clinical recommendations align with current standards, this discussion provides some interesting insight into early estimations of force. Matz's estimates contrast greatly with fairly contemporaneous rough calculations by Pearse in his 1965 paper on forceps-based traction.[53] He estimated that 9.3 lbf (41.4 N) of force would be generated due to contractions, which would then be doubled to 18.6 lbf (82.8 N) during bearing down. This 5-fold difference in the estimated force is indicative of the need to truly use an engineering approach to determine the normal range of intrauterine force values.

Intrauterine pressure can be used to calculate an effective resultant force. This has been done by a few different researchers, using different values for both the cross-sectional area over which the force is applied and the pressure itself. Both parameters will vary from delivery to delivery, and—as discussed above—intrauterine pressure will vary within a delivery. However, there have also been different choices made regarding which anatomy to use to determine the effective area over which the pressure is applied. What is the appropriate cross-sectional area to use? This has varied between the area of an average molded fetal head,[10] to a fully dilated cervix,[2] to the cross-sectional area of the fetal torso at the shoulders.[35] A discussion of the effect of these variations has been previously undertaken,[36] including the impact of modeling the head with a circular or elliptical cross-section.

Table 3 provides a summary of the published calculations for intrauterine force during the second stage of labor. Ashton-Miller and DeLancey[10] selected the cross-sectional area of a molded fetal head (approximately 63 cm^2) and combined this with intrauterine pressure values of 8.5 kPa (63.8 mmHg) during a contraction and 19 kPa (142.5 mmHg) during a contraction with bearing down. The calculated uterine force was then 54 N during a contraction and 120 N with pushing. Allen and Gurewitsch[2] used a 10 cm dilated cervix and a pressure of 10.7 kPa (80 mmHg), calculating a force of 84 N for a delivery that resulted in a temporary brachial plexus injury. In that paper, the intrauterine pressure was measured with a clinical IUPC, and the pressure during Valsalva was significantly lower (approximately 20 mmHg) than the range of values reported in Table 2 for multiparous women, even if corrected for basal pressure. Buhimschi's research group elected to use a ''pelvic inlet area'' calculated based on actual measurements of head circumference ($A = C^2/4\pi$). Using those values and a range of measured pressures, Buhimschi found that maternal forces ranged from 82 N for spontaneous contractions at the pelvic inlet to 129 N with pushing.[17] Grimm calculated variations in generated force for a range of pressures that represent uterine contractions alone as well as contractions plus pushing, using data from Lindgren.[44] She used elliptical estimates of the cross-section of the fetal body at the shoulders based on anthropometric table values for chest depth and bisacromial diameter taken from 5th, 50th, and 95th percentile infants. Forces generated by the uterus ranged from 81 N for a 50th percentile infant due to contractions alone (50 mmHg or 6.6 kPa) up to 225 N for a 95th percentile infant delivered by a primiparous patient with contractions and pushing (120 mmHg or 16 kPa).[35]

The variation in pressure that develops in the uterus is fairly easy to account for, even though there have been substantial differences found in clinical measure-

TABLE 3. Calculation of effective intrauterine force by various researchers.

Research group	Model characteristics	Intrauterine pressure (kPa)	Anatomical cross-section Used	Cross-sectional area (cm^2)	Calculated intrauterine force (N)
Allen and Gurewitsch[2]	Not specified	10.7 (80 mmHg)	Dilated cervix (ϕ = 10 cm)	78.5	84
Ashton-Miller and DeLancey[10]	Contractions only	8.5 (64 mmHg)	Fetal molded head, average (ϕ = 9 cm)	63	54
	Contractions with pushing	19 (142.5 mmHg)			120
Buhimschi[17]	Contractions only	9 (67.5 mmHg)	Pelvic inlet area based on measured head circumference	91	82
	Contractions with pushing	14.2 (106.5 mmHg)			129
Grimm[34]	Uterine contraction—primiparous	6.7 (50 mmHg)	Shoulder cross-sectional area of 50th percentile and 95th percentile infants	50th %ile Fetus—120 95th %ile Fetus - 140	50th %ile—81 95th %ile—94
	Uterine contraction—multiparous	8.7 (65 mmHg)			50th %ile—104 95th %ile—122
	Uterine contraction with pushing—primip	14.4 (108 mmHg)			50th %ile—173 95th %ile—202
	Uterine contraction w/pushing—multip	14.8 (111 mmHg)			50th %ile—178 95th %ile—207
	Uterine contraction w/pushing—end of 2nd stage—multip	15.2 (114 mmHg)			50th %ile—182 95th %ile—213
	Uterine contraction w/ pushing—end of 2nd stage—-primip	16 (120 mmHg)			50th %ile—193 95th %ile—225

ments. Determining the appropriate—and accurate—area over which the pressure is applied to generate a force is more complicated and is a focus of current debate. During the second stage of labor, is the obstructing area of the fetal "piston" the area of the dilated cervix or the cross-sectional area of the infant's torso? As amniotic fluid is retained in the uterus after the membranes are ruptured—as evidenced by the fact that an amniotic pressure can be measured and a volume of fluid typically accompanies the delivery of the infant's body—this author would argue that the body cross-sectional area is the more appropriate estimate.[35] Mathematically, the surface integral over which the pressure is applied should be used to convert intrauterine pressure to a resultant force. This should then be combined with any force components that come directly from myometrial contraction in contact with the fetal body (i.e. a direct force transfer). However, neither the surface area nor the contact force has been estimated to date. Accurate measurement of combined expulsive forces is still an area that warrants attention by researchers—at which point it may be possible to reconcile both the values presented in Table 3 and the 422 N of force that Matz[49] empirically estimated was needed to deliver an infant.

VARIATIONS IN MYOMETRIAL FORCE—EFFECTS OF SYSTEMIC CONDITIONS

The micro-to-macro connection between the tension developed in the myometrium and the force generated by the uterus is still an area that needs significant investigation. However, the underlying principal is well understood—the driving tissue-level phenomenon is the contraction of the smooth muscle of the myometrium. Anything that affects the contractility—or ability to contract—of the myometrium can be expected to impact the maximum force that can be produced by uterine contractions. Maternal pathologies or underlying conditions, such as diabetes and maternal obesity, have been seen clinically to impact the progression of labor. However, the cause of these clinical associations is not immediately apparent. Researchers have initiated studies into tissue-level biomechanics to elucidate some of the factors that may explain these observations.

In 2011, Al-Qahtani *et al.* investigated the contractility of myometrium obtained through biopsies of non-diabetic and diabetic patients undergoing an elective cesarean section.[6] Contractility of the muscle strip was assessed during a period of spontaneous, periodic contractions for the sample tissue. The researchers found a significant reduction in the amplitude and duration of the contractions for the diabetic patients compared to the non-diabetic controls. The diabetic subjects included those who suffered from Type-I diabetes diagnosed prior to pregnancy as well as those who had developed gestational diabetes. The reduced contractile ability was determined to be independent of subject age, BMI, birthweight of the infant, gestational age, and whether the diabetes was addressed through diet or insulin. Based on concurrent measurements made in this series of experiments, it was hypothesized that this difference was due to changes in calcium channel expression and signaling. There was also a small, but significant, reduction in myometrial mass between the diabetic and control subject groups. Thus, a systemic physiological change—that manifested either pre-pregnancy or antepartum—had a significant effect on the contraction ability of the myometrium, and therefore the force that the uterus would have been able to generate. This difference may explain the higher rate of cesarean sections among diabetic patients, especially those that occur due to a failure of labor to progress.[26]

Zhang *et al*. confirmed the epidemiological findings that obese women are at a higher risk for cesarean section, especially due to a delay in the first stage of labor.[72] They then studied the contractility of myometrium tissue samples obtained from 73 women undergoing elective cesarean section, who were divided into groups defined as underweight (BMI $<$ 19.9 kg m^{-2}), normal BMI (20 to 24.9 kg m^{-2}), overweight (BMI of 25 to 29.9 kg m^{-2}), or obese (BMI $\geq$ 30 kg m^{-2}). Measuring amplitude and frequency of contraction, the results indicated a significantly lower contractile force and frequency for the samples obtained from both overweight and obese women compared to those from women with normal BMI. Crankshaw recently followed up and expanded on Zhang's study.[22] Samples were taken from 74 donors during elective cesarean section and were grouped using the same cutoffs as Zhang, except that the underweight and normal groups were combined. The maximum BMI of Crackshaw's subjects was 50 kg m^{-2}, while the minimum was 18.5 kg m^{-2}. In contrast to Zhang's findings, they found that maximum amplitude and mean contractile force were positively correlated with BMI—so women who were increasingly overweight were expected to be able to generate more uterine force and higher intrauterine pressures, which should have a positive effect on the progression of labor. However, the time that was required for spontaneous contraction to be initiated in the experimental setup (time to first contraction) and the time to achieve the maximum amplitude (an indication of reaching effective contraction strength) were also positively correlated with BMI—higher BMI resulted in more time needed for contractions to begin and reach a maximum generated tension. These results may be a factor in the clinical observations that women with higher BMI have a reduced onset of spontaneous labor.[64] Zhang had not completed this broader assessment of the contractile physiology. As there are disparate results, this phenomenon does warrant further study to better understand the underlying pathophysiology for the clinical observations—are increased rates of cesarean section for overweight and obese women the result primarily of differences in labor onset and the establishment of active labor, or does the strength and frequency of uterine contractions also play a significant role?

It is interesting to note that maternal age has not been shown to have an impact on myometrial contractility for ages 25 to 40 years[9] or ages 28 to 52 years.[21] Thus, if pregnancy can be established, there is no indication that there is a higher chance of dysfunctional labor simply based on the mother's age. In addition, no statistical difference in contractility was found for myometrial samples as a function of parity.[58]

CLINICIAN-APPLIED FORCES

As a comparison with the natural forces of labor and delivery, it is helpful to be aware of the measurements of force that have been applied by clinicians in actual deliveries. A clinician might apply force to the infant through one of three basic mechanisms: their hands (after the infant's head delivers), a vacuum extractor, or forceps. Investigators have conducted research to quantify all three of these sources of traction.

The greatest amount of force that has been measured clinically has been applied through forceps. Using instrumented forceps, mean maximum traction forces of 154 to 188 N (34.7 to 42.3 lbf) were measured in non-shoulder dystocia deliveries.[50,53] Pearse documented a case of 489 N (110 lbf) being applied in one of the deliveries in his series.[53] Key to understanding the context of these measurements is that only the compliance of the birth canal and the general shape of the pelvis provided the resistance to the forceps-applied traction. There is no indication of any impact between the fetal shoulder and maternal pelvis in these sets of deliveries that may have further impeded forward progress of the fetus within the birth canal.

Traction applied through a vacuum is limited—based on the design of the vacuum—to a force equal to the vacuum pressure multiplied by the area of the vacuum cup. Two of the more commonly used

TABLE 4. Potential traction force supported through a vacuum extractor for standard sizes and generated pressures.

Vacuum extractor cup diameter (mm)	Maximum supported forceat 450 mmHg(Green zone—low) (N)	Maximum supported forceat 600 mmHg(Green zone—high) (N)
50	118	157
60	170	226
70	231	308

TABLE 5. Experimentally measured values for clinician-applied traction during an actual delivery. Data are provided as mean ± SD.

Research group	Number of subjects	Delivery characteristics	Mean peak clinician force (N)
Allen and Gonik[3]	20	Routine	46.68 ± 7.89
	7	Difficult	69.37 ± 6.71
	2	Shoulder dystocia	99.89 ± 0.00
Allen and Poggi[53]	27	Routine with epidural[a]	34.3 ± 12.5
	5	Routine without epidural	17.3 ± 8.9
Allen and Poggi[54]	13	Routine in lithotomy position[b]	32.0 ± 3.6
	14	Routine in prophylactic McRoberts' position[b]	35.5 ± 3.1
Peisner[52]	6 (5 clinicians)	Routine	88.8 ± 30 (range 47–135)
	4 (3 clinicians)	Vacuum to deliver head—then routine	57.5 ± 20.3 (range 32–79)

[a]Included two mild shoulder dystocia deliveries.
[b]Included one mild shoulder dystocia delivery.

vacuum models are the Kiwi and the Mityvac.[1] According to the manufacturers' specifications, each system has a ''green zone'' pressure of between 450 and 600 mmHg (60 to 80 kPa). For standard cup sizes between 50 and 70 mm in diameter, the maximum force that can be exerted can be calculated based on the basic equation F = P x A (Table 4). The introduction of a traction indicator in one model of vacuum allowed a study to be conducted on the actual force applied during deliveries, and 80% of the deliveries saw clinicians applying less than 113 N of traction force.[65] In only two of the study's deliveries was the maximum traction greater than 132 N. Thus, while the maximum possible force that can be applied through a vacuum is similar to what has been measured using forceps, the actual forces applied by clinicians in the delivery room tend to be substantially lower.

Two research groups have reported on clinician applied, manual traction (through the hands) in clinical deliveries. The range of measured values is summarized in Table 5. Allen, working first with Gonik and then Poggi as collaborating obstetricians, has measured the applied traction in approximately 100 deliveries.[3,55,56] Both systems measured the contact force between the physician's hands and the infant's head, and then correlated the contact force with an applied traction as measured with a simulator in a lab. While there are possible calibration errors comparing contact with a slippery fetal head to that with a dry simulator head, these studies provide the most complete set of data on clinician-applied traction. The research team found that clinicians were able to qualitatively determine how much force they applied.[56] In some shoulder dystocia deliveries, statistically more traction was applied than in normal deliveries—but this was not consistent. Average forces measured by Allen's group for normal deliveries were between 17 N (without an epidural) and 47 N. In 2011, Peisner introduced a calibrated platform that could directly measure the resultant force (magnitude and direction) applied to the infant's head and used it to characterize the force applied by eight different providers (physicians and midwives) in a total of 10 deliveries.[54] Four of the deliveries were assessed after the infant's head had been delivered via vacuum and the obstetrician shifted to manual traction. The maximum applied force for all of the deliveries ranged from 32 to 135 N. Peisner provided time-dependent plots of both the magnitude and angle of the applied force from the delivery of the head through to delivery of the body, which demonstrated that there was no consistent pattern of force application between the deliveries. Some of the variation in both the magnitude of the force and the pattern of application in this set of deliveries is likely to be due to the fact that a broad range of clinicians were involved with the study, especially as compared to the study by Allen's group. However, this demonstrates the range of ''normal'' clinician-applied force that can be expected in a routine delivery.

Using high-fidelity simulators, clinician applied forces to the infant's head during a shoulder dystocia delivery have ranged from 6 N to 250 N (mean of 106

N).[23] It is difficult to know how accurately these compare to the force that the same clinician might apply in an actual delivery room, as the simulators were designed to not allow delivery unless a particular maneuver was implemented. A study to compare forces applied in simulated deliveries to those applied in actual deliveries would be a challenge to conduct for a reasonably wide range of clinicians. Not only is it a technical challenge to measure delivery force in a clinical situation, but the variation in maternal and fetal properties is different for every delivery. However, such a study would provide a better understanding of whether the quantitative information that can be obtained from a high-fidelity simulator can be used to evaluate and inform clinical practice. Buttin[18] has also raised the issue that traditional static simulators, those that represent a limited range of scenarios, may not accurately represent the complete situation and all of the key variables, despite the ''sensation felt'' by the clinician being similar to the real world. Thus, while an important component of training regimens, until validated such simulators should not be used as representative of actual clinical responses.

Determining a true range of ''normal'' traction applied to assist with a delivery—for a range of clinicians, delivery scenarios, and both maternal and infant characteristics—would provide important data to support clinical teaching along with both development and validation of computational models of childbirth. Currently, trainees are taught through an apprenticeship model based on observation followed by supervised action. Students and new residents may place their hands over those of the attending or more senior resident to gain a sense of normal traction, which can be followed by the teacher placing their hands over the trainee's hands to provide feedback about the amount of traction applied. This apprenticeship structure is now often combined with simulator training, but the biofidelity of the simulators can vary significantly. If a system to accurately evaluate clinically-applied traction could be developed and broadly implemented, it may support improved training for all clinicians involved in supporting deliveries.

CONCLUSIONS

For 2020, it is estimated that worldwide there will be 259 births per minute.[15] However, despite the fact that childbirth is a natural physiological process that can successfully occur with varying levels of familial, midwife, or medical support, it still has a significant complication rate that can affect the immediate and long-term outcomes of both the mother and child. Engineers can provide a unique perspective in addressing the questions that surround the biomechanics of labor of delivery—from the mechanobiological to the macro level. This field of biomechanical research is still relatively new, but there is a growing and connected community of researchers. This review has focused on the current state of knowledge—and the current gaps in knowledge—regarding one of the key foundational biomechanical concepts of labor and delivery, namely the maternal and clinician-applied forces that act to move the infant from the uterus to the outside world. The goal of this review is that it will provide a consolidated source of information for individuals developing computational models of parturition as well as catalyze new directions of inquiry.

CONFLICT OF INTEREST

No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

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