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The Biomechanics of Neonatal Brachial Plexus Palsy:

How Can We Understand an Injury without Direct Validating Measurements?

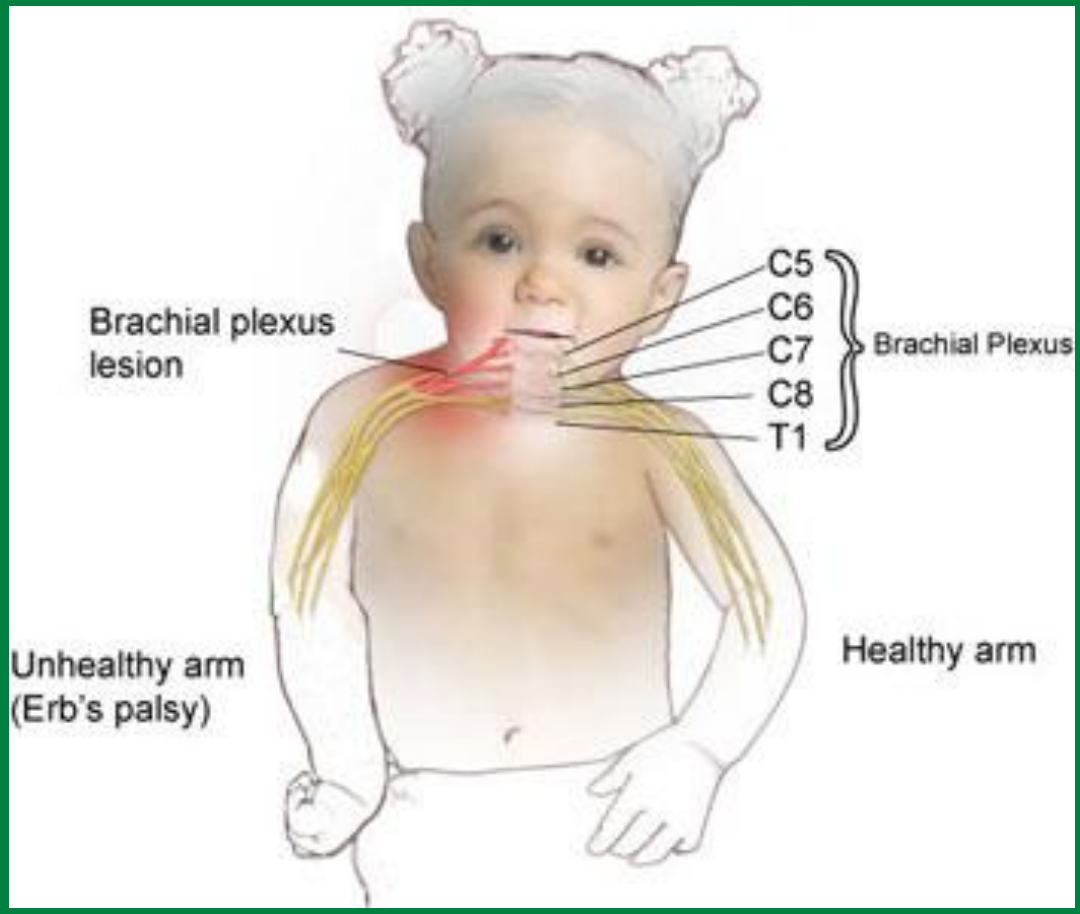
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Department of Biomedical Engineering

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What is “Neonatal Brachial Plexus Palsy?”



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Neonatal Brachial Plexus Palsy

- NBPP
- Temporary injuries occur in 1/1000 births
  - Paralysis that recovers spontaneously
  - Recovery can occur in hours or months
- Persistent injuries occur in 1/10000 births
  - Some residual injury at 12-24 months of age

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Important Concepts Related to Nerve Injury

- Nerve injuries occur along a continuum of severity
  - Neuropraxia: sustained “falling asleep” of a limb
  - Partial rupture: some nerve fibers are still connected, but amount of innervation of muscles is reduced
  - Complete rupture: no axons remain connected, chance of spontaneous healing is minimal – can be grafted
  - Avulsion: rupture at the connection of the nerve to the spinal cord, which does not provide any nerve to which a graft can be connected

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Important Questions

- What are the potential mechanisms of injury in neonatal brachial plexus palsy?
- What is the injury threshold for the infant brachial plexus?
- How can injury risk be reduced?

How can we study these questions?

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Studies That Can't Be Done

- Cadaver studies on infants
  - Specimens not available
- Clinical studies that might put an infant or mother at greater risk
- Observational studies with sufficient power to draw conclusions
  - Semi-quantitative study in Sweden of 31,000 deliveries had 18 persistent injuries

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Studies That Can Be Done

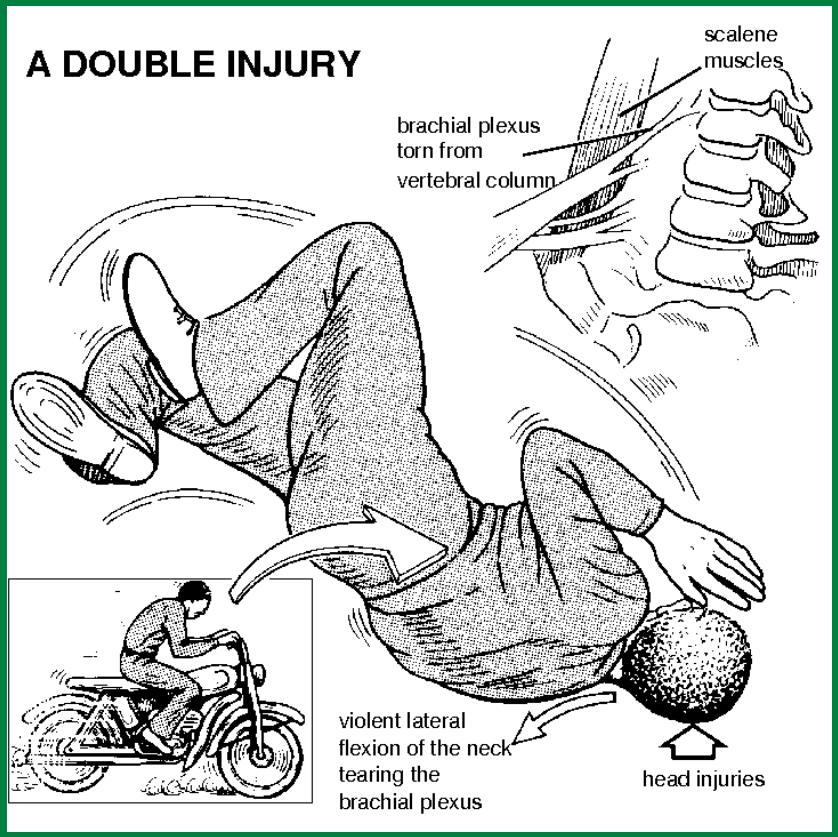
- Models
  - Computer and physical
- Surrogates
  - Adult case studies
  - Adult cadavers
  - Animals
- Limited clinical observations
  - Typically retrospective
  - Generally based on standard practice, not actions that are thought to potentially increase risk of injury

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How Can the Brachial Plexus Be Stretched?

I. Moving the head away from the shoulder

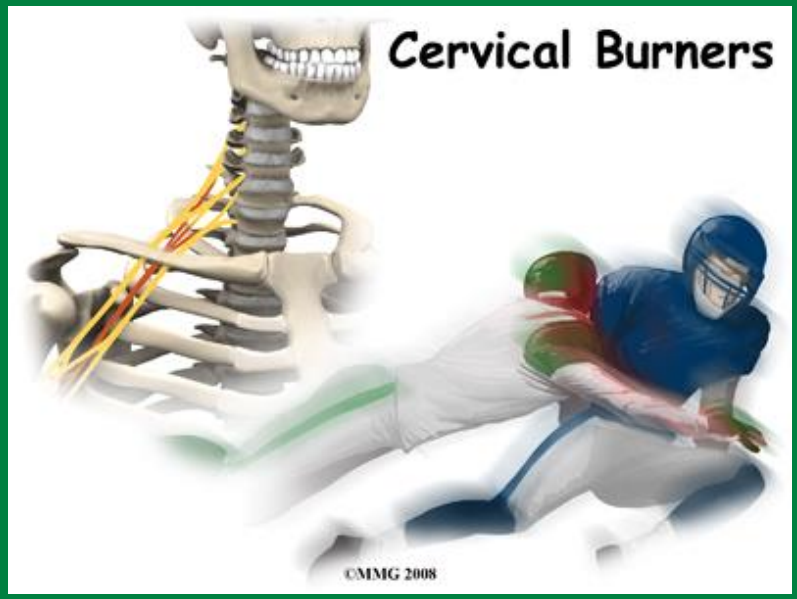


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How Can the Brachial Plexus Be Stretched?

II. Moving the shoulder away from the head

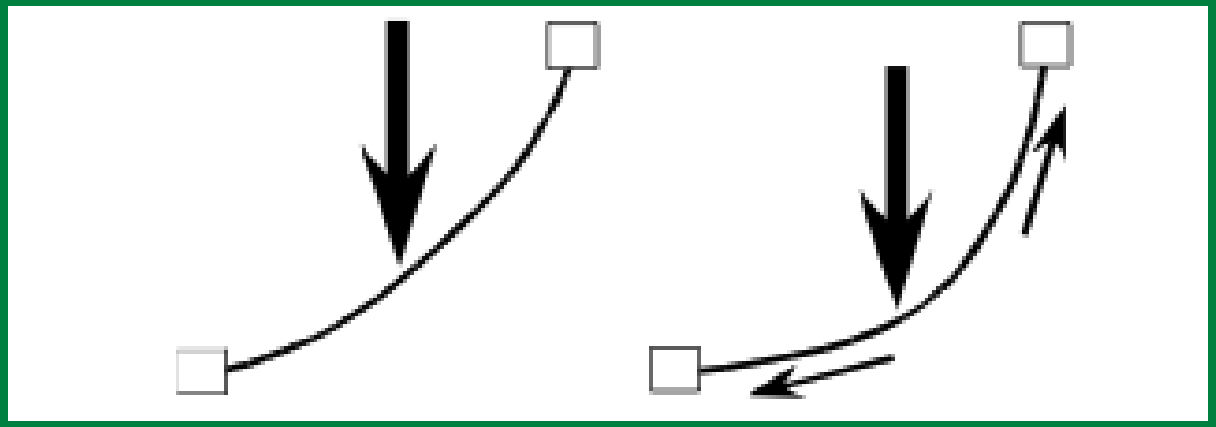


Shoulder is stopped, spine and/or momentum moves head forward



How Can the Brachial Plexus Be Stretched?

III. Pushing down on the middle of the nerve



The ends of the brachial plexus are essentially fixed points - pushing down in the middle of the "string" that connects the points will cause it to stretch



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How Can the Brachial Plexus Be Stretched?

IV. Pulling the arm away from the body

*Pulling the abducted arm away from the body typically injures the lower plexus (C8/T1) before the upper plexus based on how the nerves are put in tension**

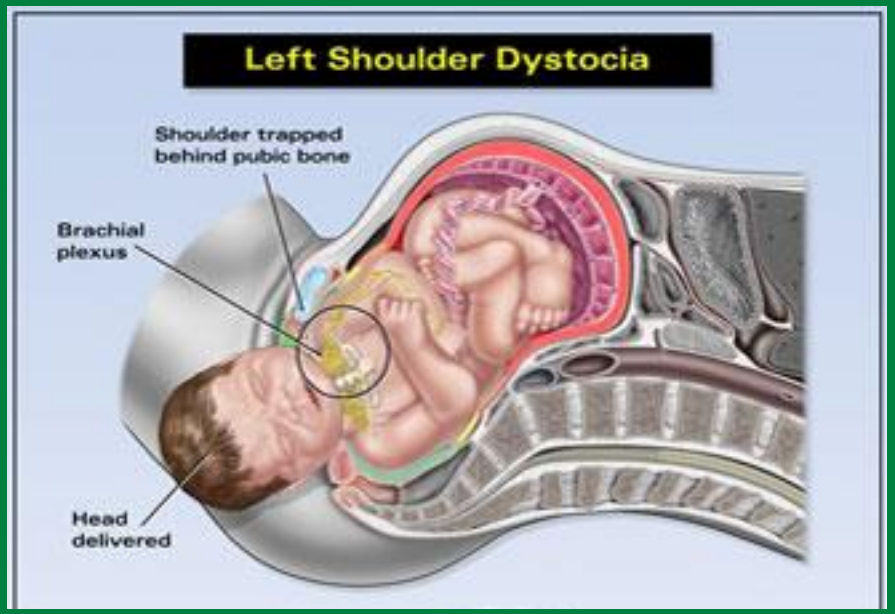


Coene, Clin Neurol Neurosurg, 95:S24, 1993



What are the Causes of NBPP?

- Strong association with shoulder dystocia
  - Obstetrical emergency where the shoulders of an infant do not spontaneously deliver
  - Often diagnosed by a “turtle sign” – infant’s head pulls back against perineum



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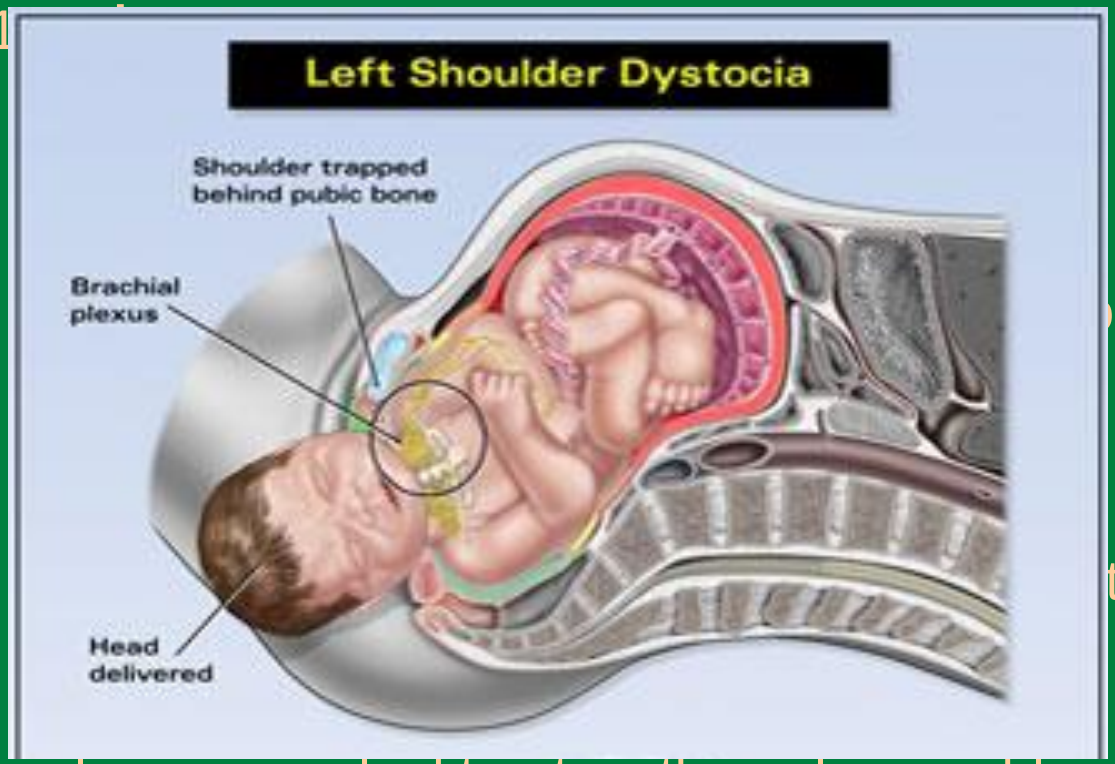
Cause of NBPP: A Progression of Theories

- Before 1990, generally accepted that injury was due to clinician applied traction (bending) to an infant's head and neck when the shoulder was impacted
- Teaching stressed:
  - Not applying bending to neck
  - Use of maneuvers to release shoulder from impaction
- Observational infant cadaver studies had demonstrated this mechanism
- No studies had ever been done to evaluate other causes of BP stretch



Cause of NBPP: A Progression of Theories

- 1
- Is clinician-applied traction the only possible mechanism of injury?



*Gherman, AJOG, 180:1303, 1999; **AJOG, 195:657, 2006
***Ouzounian, Obst Gyn, 89:139, 1997. MacKenzie, Obst Gyn, 110:1059, 2007

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Cause of NBPP – What We Knew in 1990s

- Lateral bending of the infant's neck can stretch the brachial plexus and cause NBPP
- Traction by the clinician along the axis of the spine reduces stretch in the brachial plexus compared to bending the neck
- Various maneuvers developed based on clinical observation help to relieve a shoulder dystocia

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Cause of NBPP – What We Knew in 1990s

- Intrauterine pressure from contractions and pushing can be about 120 mmHg – generating about 140 N of force for an average sized infant
- Clinician-applied traction (measured in limited number of clinical deliveries) is typically 40 N in normal deliveries, up to 80 N in difficult or shoulder dystocia deliveries
- Permanent NBPP seen in:
  - Anterior shoulder
  - Posterior shoulder

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Cause of NBPP – What We Didn't Know in 1990s

- What effect do maternal forces have on the brachial plexus when an infant's shoulder gets stuck?
- How much stretch do various amounts and types of clinician-applied traction cause to the brachial plexus?
- How do the maneuvers to release a shoulder dystocia affect stretch in the BP and/or necessary force for delivery?
- How much force or stretch is required to injure the brachial plexus?

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Answering the Remaining Questions through Modeling

- Experimental work on cadaver infants and clinical deliveries is challenging
- Many current biomechanical studies use physical or computer models to try and understand the mechanisms of NBPP and the effect of various maneuvers/interventions on reducing the risk of injury
- Things to look for:
  - *How closely do properties of the model mimic real life?*
  - *Are the conclusions reasonable given the limitations of the model?*

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Current Models of NBPP Pathomechanics

Computer Model	Physical Model
Gonik & Grimm	Gurewitsch & Allen
Published 2003 & 2010	Published 2005 & 2007
AJOG 189(4), 2003	*IEEE Engg in Med & Biol Mag, Dec 2005*
AJOG 203, 2010	*AJOG, 195, 2005*
	AJOG 196, 2007

How do the necessary delivery force and the resulting BP stretch vary for different sources of force and maneuvers?



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Computer Modeling

- Benefits:
  - Do not need to find physical structures that mimic the properties of the real infant and mother
  - Know exactly what changes from one “experiment” to the next
- Drawbacks:
  - Does not allow the interaction of different real-world clinicians

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Building a Computer Model of NBPP

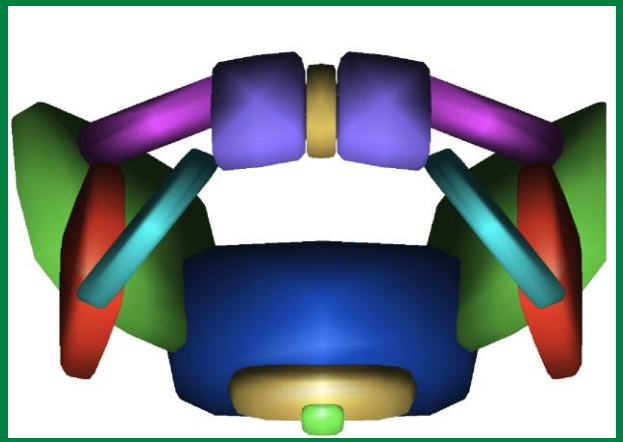
- Focus on shoulder dystocia as key contributing phenomenon
- MADYMO rigid body modeling
  - Level of detail (and computational power) for FEA not necessary at this time
- What are appropriate model inputs?
  - What do we know?
  - What can we estimate?
  - What do we have to guestimate?



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Building a Computer Model of NBPP - Anatomy

- Pick a representative anatomy and decide on important parts of model
- 50th %ile female pelvis
  - Remainder of female skeletal anatomy does not come into play
  - Modeling dynamic uterine environment more complex than needed

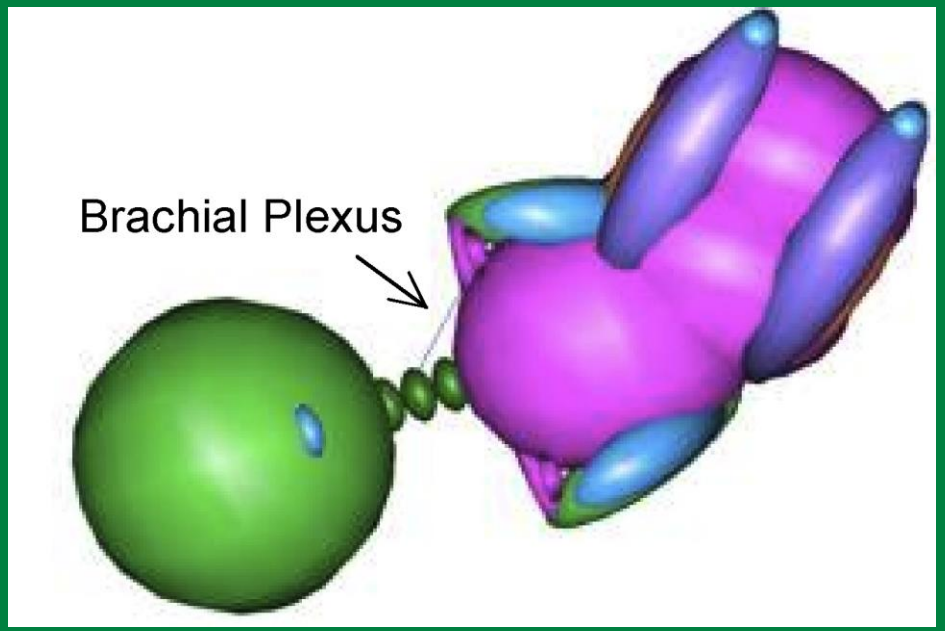


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Building a Computer Model of NBPP - Anatomy

- Pick a representative anatomy and decide on important parts of model
- 90th %ile infant
  - Primary focus on neck and shoulder



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Building a Computer Model of NBPP - Anatomy

- Anatomic values taken from anthropomorphic tables
  - Pelvic size – inlet and outlet
  - Infant
    - Mass
    - Size
    - Limb and torso length
- For infant model, started work based on 9-month old crash test dummy model in MADYMO
- “Brachial plexus” added as single nerve from C5/6 junction to proximal arm

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Building a Computer Model of NBPP – Material Properties

- Will affect how model responds to applied or resultant forces
- Maternal model –
  - Assume rigid
  - Does not include maternal soft tissues – effect of these will need to be included in some way

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Building a Computer Model of NBPP – Material Properties

- Infant model - most important material properties for these dynamics
  - Shoulder stiffness
  - Neck stiffness
  - Brachial plexus stiffness
- *There are no established values for the material properties of human infant tissues or structures!*

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Building a Computer Model of NBPP – Material Properties

- Infant shoulder stiffness – how does the multi-segment shoulder deform in response to force?
  - Animal data not relevant
  - No infant data
  - How can we work from adult data?
- Stiffness is both related to both material and structural properties
  - Properties of healthy bone, ligament, and muscle reasonably steady with age
  - Set shoulder joint stiffness at 2.5% of adult values based on change in geometry



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Building a Computer Model of NBPP – Material Properties

- Effect of choice of stiffness
  - Initial model (*AJOG*, April 2003) used the standard ATD shoulder
  - Updated model (*AJOG*, October 2003) used the biofidelic shoulder
  - Maternal force necessary to deliver the infant dropped from 400 N to 125 N

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Building a Computer Model of NBPP – Material Properties

- Neck Stiffness – how does the neck deform when subjected to tension or bending?
  - Very limited data from infants
  - What is an appropriate and available surrogate?
- Caprine (goat) model used by MCW to evaluate infant neck stiffness for child safety seat evaluation
  - Holds head erect
  - Comparison with later human values from Duke validates caprine model



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Building a Computer Model of NBPP – Material Properties

- Model neck modified to consist of 7 independent cervical vertebrae
- Neck stiffness defines the tensile and bending stiffness between each pair of cervical vertebrae
- Use of caprine data may overestimate neck stiffness and under-predict the stretch to the brachial plexus

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Building a Computer Model of NBPP – Material Properties

- Nerve stiffness – how does the brachial plexus respond when the neck and shoulder angle widens?
  - No data on infant brachial plexus
  - What is an appropriate surrogate?
- Stiffness
  - “Living” tissue – minimal tissue degradation
  - Peripheral nerve
  - Mammalian

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Building a Computer Model of NBPP – Material Properties

- Excellent data available on rabbit tibial nerve model from Pittsburgh
  - Stiffness immediately postmortem
  - Show that the “zero-point” for in situ strain is actually about 11%

rium, as well as the nerve fibers in the endoneurium, seemed intact, except for nerve fiber ‘‘herniations’’ through defects in the perineurial sheaths. Occasionally, coiled epineural tissue was observed (Fig. 5), suggesting possible failure of this tissue during stretching and its relaxation prior to fixation; however, this was observed much less frequently than disrupted perineuria. Extravasated erythrocytes were also observed in the epineurial space of stretched nerves. In the transverse sections of the stretched specimens, several fascicles that ap-

ments (Figs. 3B, 4
rupted nerve fibers
perineurium.

Stretch injury to
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6.28 N

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Building a Computer Model of NBPP – Material Properties

- Effects of choice of surrogate for nerve properties
  - Adult nerves are more myelinated than infant nerves
    - Stiffness expected to be higher in adult nerves
  - Immediate postmortem tests will be most similar to living tissue
  - Human brachial plexus would be ideal – but mammalian peripheral nerve should be similar

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Effects of Material Property Choices

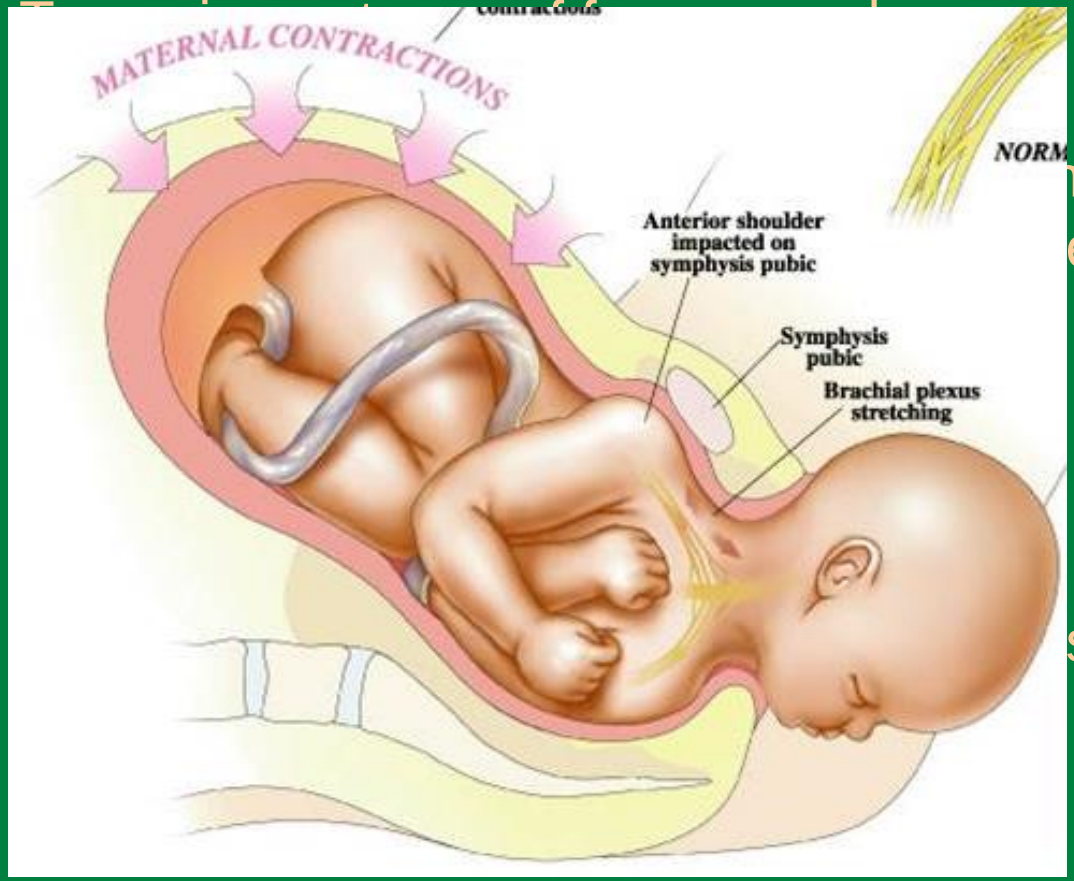
- Estimates required as no data exists on actual neonatal structures
- Effect of estimates are minimized if model is used to compare response holding properties constant
  - “Apples to Apples” comparison
  - If nerve is modeled as stiffer than reality, then predicted stretch will be lower in all cases – but trends in terms of what type of forces produce higher stretch should remain constant
- Model cannot be used to predict response of a particular child – as the child’s tissue properties are not (and cannot) be known

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Building a Computer Model of NBPP – Applied Forces

-
-

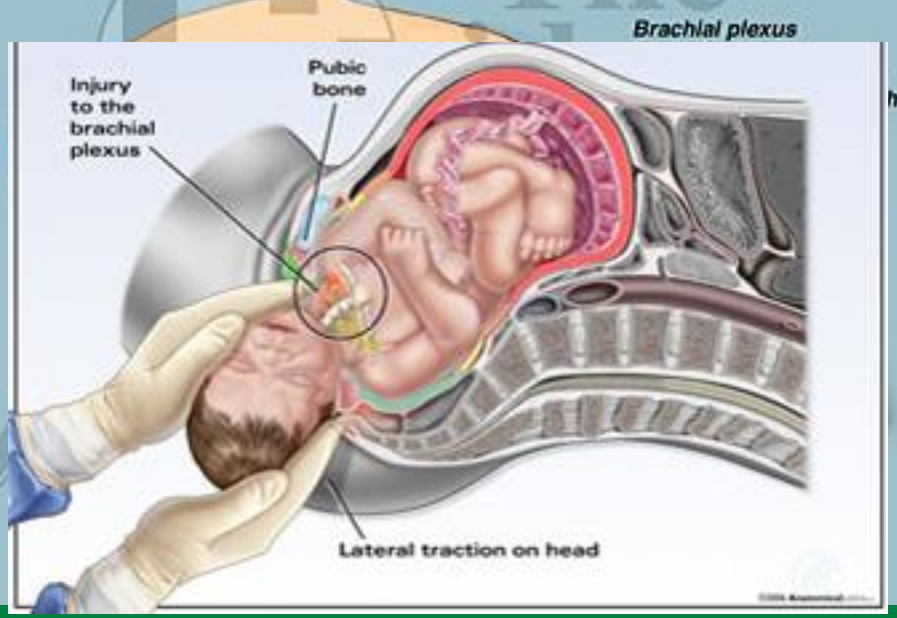


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Building a Computer Model of NBPP – Applied Forces

- Clinician (exogenous): assistive traction applied by the physician or nurse midwife
  - Axial – without bending infant's neck
-



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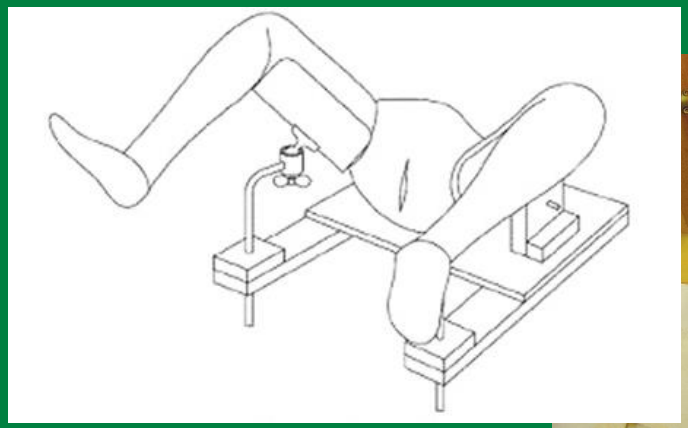
Physical Modeling

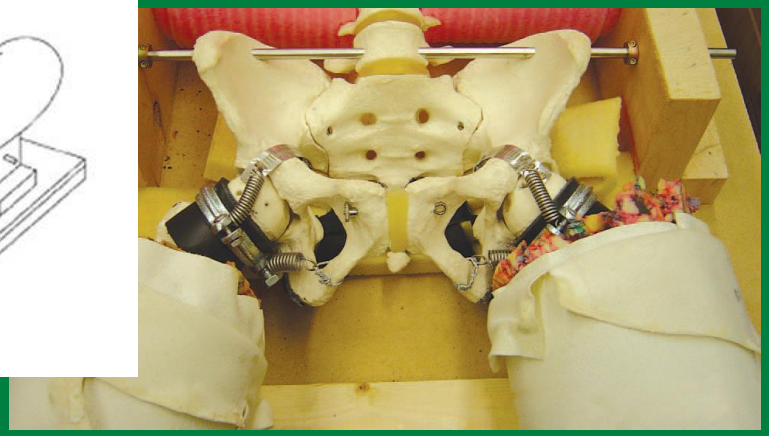
- Benefits:
  - Allows real world visualization
  - Allows interaction by clinicians
- Limitations:
  - Must find physical structures that match biological tissues
  - Chance of increased variabillity in “input” of human-controlled parameters

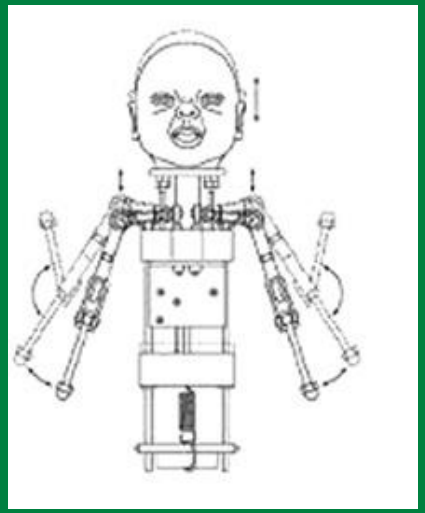
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Physical Model

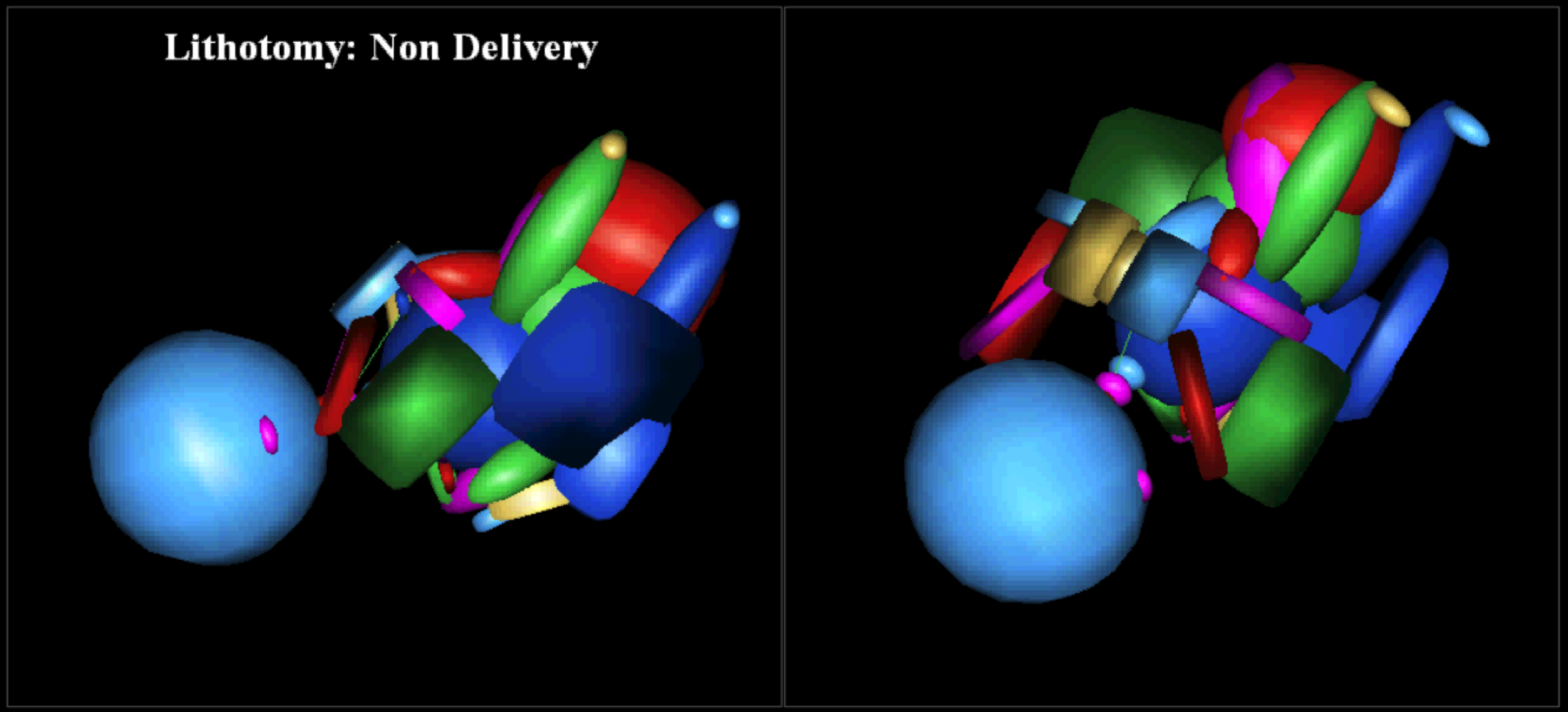




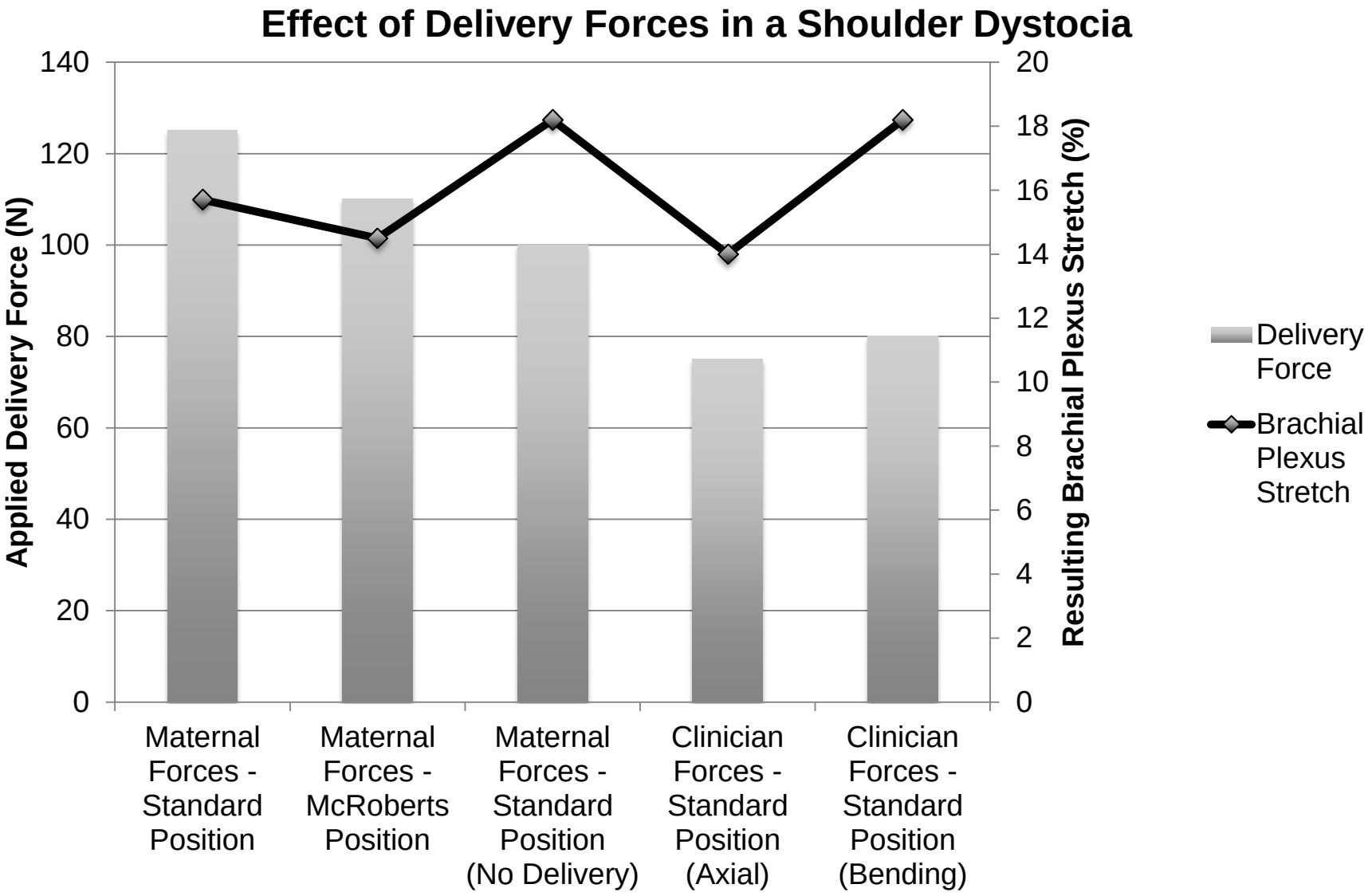




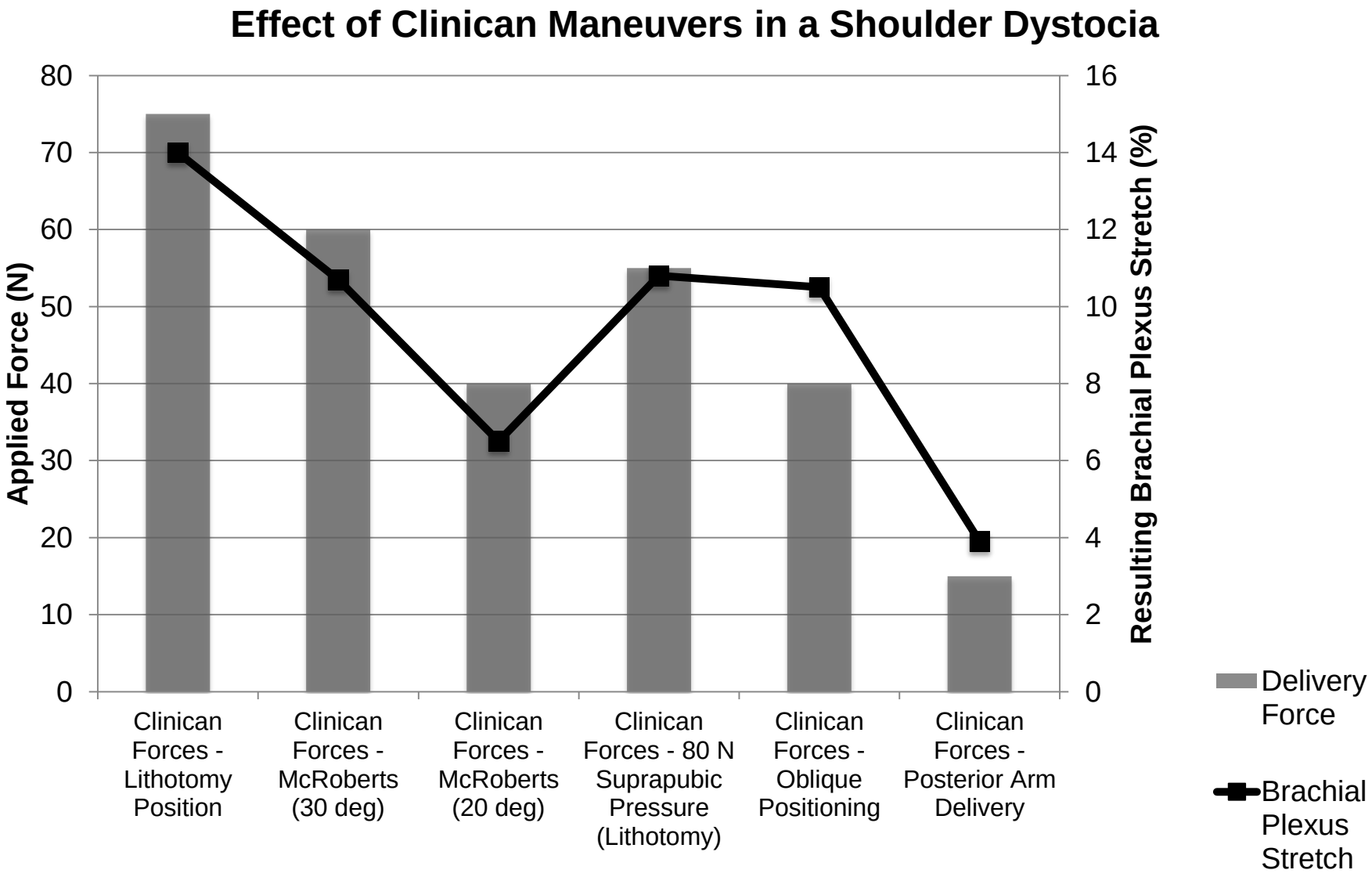
Lithotomy: Non Delivery



Computer Modeling: NBPP Predictions



Computer Modeling: NBPP Predictions



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NBPP Computer Modeling – Conclusions Part 1

- Lateral bending and maternal forces (shoulder remains stuck) both predicted to cause 18.2% stretch in the brachial plexus
- Axial traction and use of maneuvers require less clinician force and reduce subsequent BP stretch

If 18% stretch will result in a nerve rupture in a particular infant, then the injury can occur as a result of maternal forces alone

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Computer Modeling: Gonik and Grimm Limitations

- Not all soft tissue resistances included
  - Resistance tuned to obtain reasonable delivery forces
  - Will have same effect on all types of delivery force applied
  - Trends will still hold true
- Validation limited
  - No cadaver studies to compare to directly
  - Delivery forces (clinician and maternal) similar to what has been seen clinically
  - Effect of maneuvers matches that predicted with physical model
  - Restitution of infant as shoulder delivers is based on physics and is not prescribed

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How do Maternal Forces Stretch the Brachial Plexus?

- Key question – counterintuitive for many clinicians!
- Maternal forces act on the torso of the infant -- how do those stretch the BP?
- Primary mechanism: spinal loading

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How do Maternal Forces Stretch the Brachial Plexus?

- **Spinal loading: driving force from the rear
- Loading to the infant's bottom through the uterus will continue up spine
- Spine in compression acts as a solid rod
  - Will transmit force through to cervical spine, continuing to move head forward
- If shoulder stuck, force will still try to move spine/neck/head forward and will widen angle between shoulder and neck



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What is the Injury Threshold for the Neonatal Brachial Plexus?

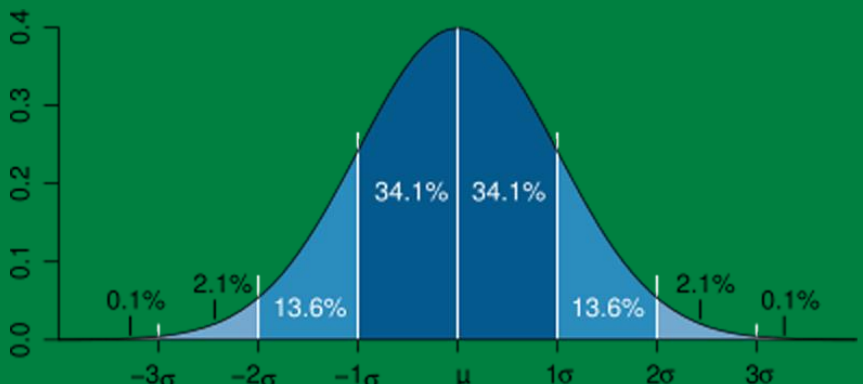
- Final piece of the puzzle
  - Will the predicted stretch from the computer model result in rupture of a brachial plexus nerve root?
- Data does not exist for human, infant nerve properties – what is an appropriate surrogate?

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Susceptibility to Brachial Plexus Injuries

- Singh *et al.* (2006)*:
  - Spinal nerve roots of rats fail at a wide range of strains
  - 29+/- 9% failure strain - what does that mean?
    - 2/3 of nerves will fail between 20 and 38% stretch
    - 1/6 of nerves will fail between 11 and 20% stretch

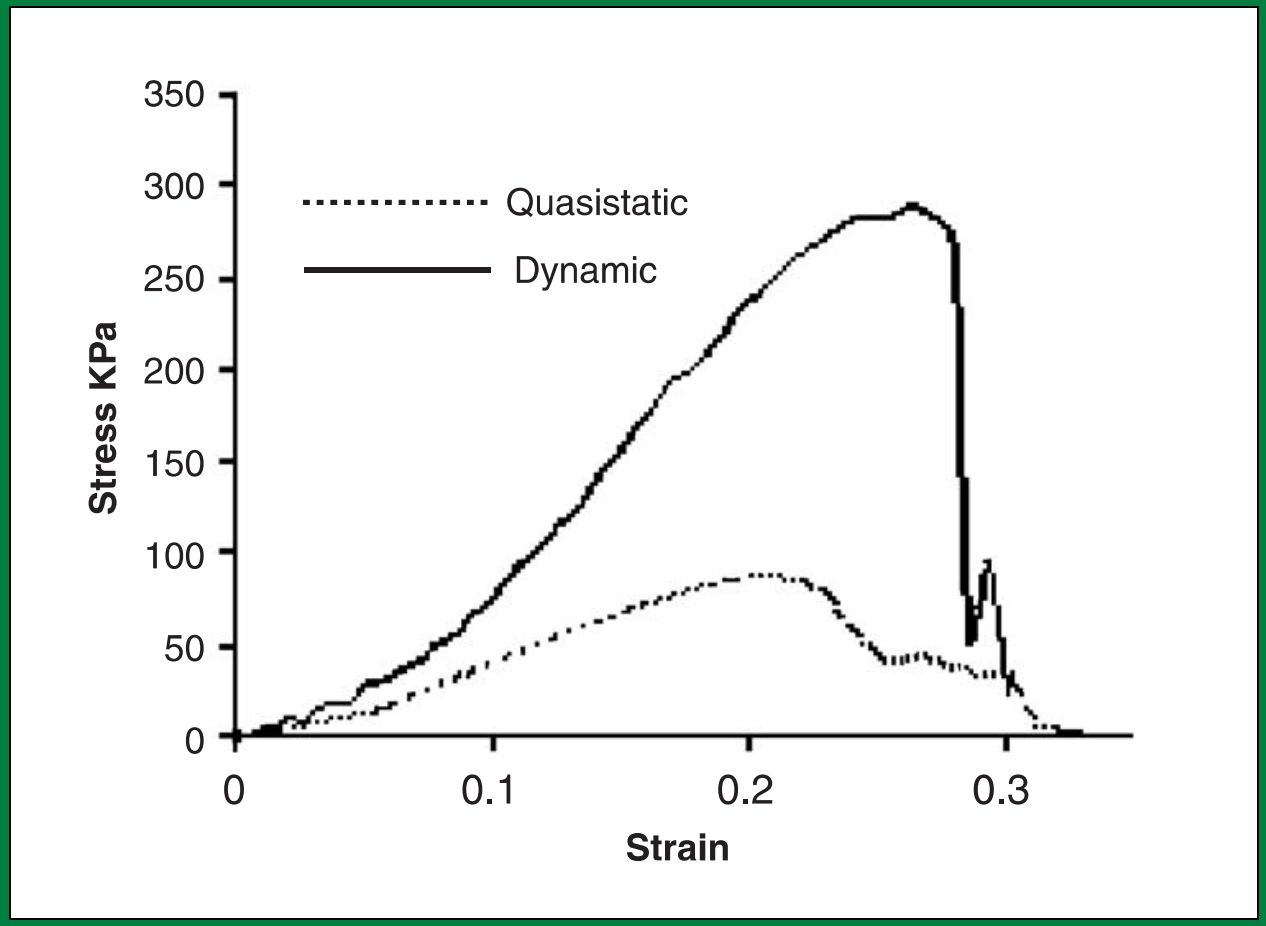


Singh, J Biomech, 39:1669, 2006

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Rupture Behavior of Spinal Nerve Roots



Singh, J Biomech, 39:1669, 2006

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Can Maternal Forces Cause Permanent NBPP?

- Combining modeling predictions and Singh results:
  - Maternal forces are predicted to cause stretch in the brachial plexus in the mid-teen percents when the shoulder becomes impacted on the maternal pelvis
  - A minority of the population are expected to experience nerve rupture at strains in the mid-teen percents

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Impact of Research Results

- Clinician training
  - Avoid bending the neck
  - Practice maneuvers
  - Minimize maternal pushing until shoulder impaction reduced
- Medicolegal
  - Previously claimed that all NBPP the fault of clinicians
  - Current evidence indicates that persistant NBPP can occur during normal delivery process

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Impact of Research Results

- Hotly debated area of research
- Will benefit from collaboration between:
  - Obstetricians
  - Neurosurgeons & Neurologists
  - Engineers
    - Only a handful worldwide investigating this



Current Agreement on NBPP

- The primary force that injures the brachial plexus during the birth process is tension (pulling) on the nerve
- Injuries can happen in the absence of clinician-applied traction
- Stretch to the brachial plexus occurs during deliveries as a result of maternal forces alone
- BPI can occur to anterior or posterior shoulders and with or without a clinical shoulder dystocia

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Current Debates on NBPP

- Is the pulling of the nerve that causes injury primarily due to clinician-applied traction or due to maternal forces?
- Can permanent injuries be caused by maternal forces alone?

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Questions?

