Introduction to Neuromuscular Disorders in Cerebral Palsy and Clinical Gait Analysis

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Muybridge used chronophotography, a technique invented by French photographer, Etienne-Jules Maray (1830-1904). Muybridge set up a series of cameras with threads attached, as the horse galloped by the cameras were triggered.

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Teaching Points

• Four Neuromuscular Disorders of *Spastic* Cerebral Palsy

• Phases of the Gait Cycle

• Kinematic, Kinetic and EMG measures of Gait

• Analysis of Common Gait Disorders

• Upper Limb Kinematics of Reach & Grasp Cycle
Motion & Gait Laboratory

A Clinical Service and Research Laboratory

Biomechanical Analysis of Gait and Upper Limb Function

Kinematics: 3-D Joint motion recorded by

8 digital motion capture cameras

Kinetics: Forces across joints

calculated from ground reaction force & kinematics

EMG: muscle activity while walking or reaching

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Cerebral Palsy (CP)

• A disorder of the development of movement and posture resulting from a brain injury around the time of birth.

• 3/1000 children in general population have CP

• 50-150/1000 children born very preterm have CP

• Types of CP
  
  Spastic  Most common form of CP
  Dyskinetic  Involuntary movements
  Ataxic  Poor balance, accuracy

• Gait Analysis identifies specific deficits, guides treatment.
Neuromuscular Disorders in Spastic CP

Arise from brain injury and subsequent loss of descending neural activation & inhibition

- Muscle Weakness
- Short Muscle-tendon Length
- Muscle Spasticity
- Impaired Selective Motor Control

Spastic CP may occur with Dyskinetic & Ataxic CP

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Neuromuscular Disorders

Arise from Brain Injury in Spastic CP

Cortical Spinal Tract (CST) motor neurons descend in Posterior Limbs of Internal Capsule (PLIC)

PLIC microstructure in preterm infants predicts neurodevelopment

Rose et al, 2005, 2007 Dev Med Child Neurol; Rose et. al, 2015 Ped Res

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Neuromuscular Disorders Arise from Brain Injury in Spastic CP

Neuroimaging research on neonatal brain region microstructure assessed on DTI using exhaustive feature selection and linear regression - predicts motor development assessed on BSID-III

BSID-III Composite Motor Score Predicted by L posterior-limb-of-internal-capsule, R parahippocampal gyrus, R middle temporal gyrus.

Model accounted for 32% variance in Motor Composite Score (LOOCV $R^2=0.317$).

Rose et al., 2015 Ped Res; Schadl et al., 2017 NIMG Clinical
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Neuromuscular Disorders

Arise from Brain Injury in Spastic CP

Injury to developing brain  ↓ motor neuron firing rate  ↑ type-1 fibers, size variation


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Neuromuscular Disorders in Spastic CP

Weakness

↓ Max Neuromuscular Activation: Max EMG / M-wave

Rose & McGill, 2005 *Dev Med Child Neurol*

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Neuromuscular Disorders in Spastic CP

Weakness

\[ \downarrow \text{Max Neuromuscular Activation} \]

Max Neuromuscular Activation (% M-wave)

Rose & McGill, 2005 *Dev Med Child Neurol*

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Neuromuscular Disorders in Spastic CP Weakness

↓ Projected Max Motor-unit Firing Rates

Rose & McGill, 2005  *Dev Med Child Neurol*

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Neuromuscular Disorders in Spastic CP

Short Muscle-tendon Unit

- Growth Rate Discrepancy ↓ Muscle to Bone Length Ratio
- Muscle Atrophy & Weakness

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Obligatory co-activation of flexors or extensors

Mediated by Red Nucleus and Rubrospinal Tract:

Develops in infancy, less prominent in adults

Develops after Cortical Spinal Tract Injury, assessed on DTI

Acute stroke patients  Yeo & Jang (2010)
Chronic stroke patients  Radlinska et al. (2010)

Activates synergist muscles - flexion and extension patterns

↑Flexors  ↓Extensors  Belhaj-Saif & Cheney (2000)
↑Extensors  ↓Flexors  Yang et al. (2011)

Provides imperfect motor compensation

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Neuromuscular Disorders in Spastic CP

Review

- Muscle Weakness
- Short Muscle-tendon Length
- Muscle Spasticity
- Impaired Selective Motor Control
Neuromuscular Disorders

Result in *Gait Disorders*

Gait Analysis

- Identifies abnormal gait biomechanics
- Identifies neuromuscular contributions to gait
- Provides treatment recommendations
Gait disorders are analyzed in relation to the gait cycle

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Gait Events

Stance Phase

Initial contact - Toe-off

**Early Stance:** Double Limb Support  Initial contact - opposite toe-off

**Mid Stance:** Single Limb Support  Opposite toe-off - opposite initial contact

**Terminal Stance:** Double Limb Support  Opposite initial contact - toe-off

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Gait Events

Swing Phase

Toe-off - Initial contact

Early Swing: Peak knee flexion of 60 degrees

Mid Swing: Rapid knee extension – tibia perpendicular to ground

Terminal Swing: Knee extends, limb decelerates prior to initial contact

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Gait Temporal-spatial Parameters

**Stride length:** Distance from heel to heel of a single limb

**Step Length:** Distance from heel to opposite side heel

**Cadence:** Number of steps per unit time

**Walking velocity:** \( \text{step length} \times \text{cadence} \)

**Step width:** Mediolateral distance between the two heels

**Foot progression angle:** Foot longitudinal axis vs. gait progression
Stance Phase

3 Foot & Ankle Rockers


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Initial Contact

- Heel First Contact
Mid-Stance

- Controlled Tibial Advancement
Terminal-Stance

- Locked Ankle
- Heel Rise
- Trailing Limb
Stance Phase Gait Abnormality
Flexed-knee Gait
Unrestrained ankle rocker & absent forefoot rocker

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Swing

- Peak knee flexion in early swing
- Rapid knee extension in late swing
Gait Analysis: Kinematics & Kinetics

Kinematics: 3D Joint Motion
- 8 Digital Motion Capture Cameras
- Records Position of Light Reflective Markers

Kinetics: Forces passing through Joints
- Force Plate Embedded in Floor
- Records Ground Reaction Force (GRF) Vectors
  
*Calculated from GRF & Kinematics*

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Gait Kinematics & Kinetics

Planes of Motion

**Sagittal Plane** (Side View)
- flexion-extension
- dorsi-plantarflexion

**Frontal Plane** (Coronal)
- adduction-abduction
- inversion-eversion

**Transverse Plane** (Axial)
- medial-lateral rotation

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Gait Kinematics

Frontal                    Sagittal                    Transverse

CP

Normal

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Gait Kinetics

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Gait Kinetics

• Normal ankle plantarflexor moments peaks in terminal stance

• Increased plantar flexor moment in loading “double bump” due to plantar flexion at initial contact, toe-walking in CP

• Decreased moment in terminal stance associated with a reduced forefoot rocker, reduced forward momentum at toe-off.
Gait Muscle Activity

Stance

Swing

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Muscle Activity Recorded on EMG

Hip & Knee Extensors:
- Gluteus Maximus & Medius
- Hamstrings
  - Semitendinosus
  - Semimembranosus
- Biceps Femoris
- Quadriceps
  - Rectus Femoris
  - Vastus Lateralis & Medialis

Ankle Plantarflexors & Dorsiflexors:
- Gastrocnemius & Soleus
- Tibialis Anterior

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Gait EMG

Normal Electromyographic Data

- Iliopsoas
- Iliacus
- Sartorius
- Gracilis
- Rectus Femoris
- Adductor Longus
- Adductor Brevis
- Adductor Magnus
- Vastus Intermedius
- Vastus Lateralis
- Vastus Medialis
- Tensor Fasciae Latae
- Gluteus Maximus
- Semitendinosus
- Semimembranosus
- Gluteus Medius
- Gluteus Minimus
- L.H. Biceps Femoris
- S.H. Biceps Femoris
- Tibialis Anterior
- Extensor Digitorum Longus
- Extensor Hallucis Longus
- Gastrocnemius
- Soleus
- Popliteus
- Flexor Digitorum Longus
- Flexor Hallucis Longus
- Tibialis Posterior
- Peroneus Longus
- Peroneus Brevis

Normal

CP

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Diplegic Spastic Cerebral Palsy

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Diplegic Spastic Cerebral Palsy

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Kinematics

- Nearly normal hip motion
- Increased knee flexion at IC and stance
- Reduced peak knee flexion in swing
- Increased plantar flexion in stance & swing
- Internally rotated foot progression
Kinetics

- Normal ankle plantarflexor moment peaks in terminal stance

- Increased plantar flexor moment in loading “double bump” due to increased plantar flexion at initial contact and toe-walking

- Decreased moment in terminal stance associated with a reduced forefoot rocker, reduced forward momentum at toe-off

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3D Kinematics & Dynamic EMG

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Energy Expenditure

Energy Expenditure Index

\[
EEI = \frac{\text{Walking Heart Rate} - \text{Resting Heart Rate}}{\text{Walking Speed}}
\]

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Postural Balance

- Force Plate Center of Pressure
- Postural Sway with Eyes Open/Closed

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Diplegic Cerebral Palsy
Gait Kinematics

Frontal        Sagittal        Transverse

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Computer models are generated from gait kinematics (joint motion) and kinetics (joint forces) and reveal the biomechanical features that influence gait.

The changing muscle lengths during gait are calculated using the computer model. Muscles that are too short and limit gait can be identified and selected for treatment.

Delp et al, 2005

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Biomechanical Model

Hamstrings’ Length & Lengthening Velocity

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Gait EMG

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Pathologic Gait

Neuromuscular Conditions: CP, Stroke, TBI

• Dropfoot
• Equinus
• Equinovarus
• Flexed-knee Gait
  Pseudo-equinus (knees bent, ankles at neutral, forefoot contact)
  Jumped (knees bent, ankles true equinus)
  Crouch (knees bent, ankles dorsiflexed)
• Stiff–knee gait (inadequate peak knee flexion in swing)
Pathologic Gait

- Trendelenburg - *weak hip abductors* - ipsilateral trunk lean, contralateral pelvic drop
- Coxalgic – *painful hip* - ipsilateral trunk lean
- Antalgic – *painful joint* - reduced loading, short stance
- Quad Avoidance – *weak knee* - remains extended in stance, swing
Pathologic Hip Gait

Trendelenburg Gait

Weak hip abductors
Contralateral pelvic drop
Ipsilateral trunk lean
Pathologic Hip Gait

Trendelenburg (weak) versus Coxalgic Gait (pain)

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Pathologic Hip Gait *Biomechanics*

Lateral Trunk Lean Shifts Center of Mass towards Hip Joint

Reduces Hip Joint Reaction Force = abductor force + body weight

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Antalgic Gait

Painful hip, knee, foot

• Reduced loading on affected limb by decreasing stance time
• Example - ‘stone in your shoe’
• Shortens stance phase time
• Lengthens swing phase time
• Lengthens step length - asymmetric step length
Quad Avoidance Gait

Weak Quadriceps

• Knee remains extended throughout gait cycle
• Avoids demand on quadriceps at initial contact
• Stiff-knee gait avoids knee flexion in swing
• Reduces foot clearance in swing

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Gait Technology: FES-assisted Gait

Hip & Knee Extensors:
- *Gluteus Maximus & Medius*

Hamstrings
- Semitendinosus
- *Semimembranosus*
- *Biceps Femoris*

Quadriiceps
- Rectus Femoris
- *Vastus Lateralis & Medialis*

Calf
- *Soleus*

Ankle Dorsiflexors:
- *Tibialis Anterior*
Multichannel FES-assisted Gait

**Gait Event**
- Double limb support (IC - OTO)
- Single limb support (OTO - OFC)
- Swing (TO – IC)
- Terminal Swing (Peak knee flexion - IC)

**Target Muscles**
- Gluteus Max & Med, Quads
- Soleus
- Tibialis Anterior
- Quads

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Multichannel FES-assisted Gait
Restorative Therapies, Inc. Xcite RT50z

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Baseline

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Multichannel FES-assisted Gait

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Multichannel FES-assisted Gait Kinematics

Participant 1
Dx: Diplegic CP, GA-at-birth 28 weeks
Age: 10 years; Sex: female
Orthotic: AFO bilateral
Side: Left Leg

Participant 2
Dx: Diplegic CP, GA-at-birth 24 weeks
Age: 13 years; Sex: male
Orthotic: AFO bilateral
Side: Left Leg

Participant 3
Dx: Hemiplegic CP, GA-at-birth 40 weeks
Age: 11 years; Sex: male
Orthotic: None
Side: Right Leg

NMES Setting: 40 Hz, 50 µs, 30mA
NMES Timing:

GDI
Velocity (cm/sec)
Baseline
NMES
65.2
96.7
65.4
78.4

Baseline
NMES
66.9
34.7
74.5
80.3

Baseline
NMES
81.5
106.9
84.9
99.8

Normal
Baseline
NMES
50
40
20
0
-20
Ext - Flx

Hip Flex/Extention

0
20
40
60
80
100

50
40
20
0
-20
Ext - Flx

Knee Flex/Extention

0
20
40
60
80
100

50
40
20
0
-20
Ext - Flx

Pla - Dor

30
40
10
20
0
-20
-10
-30
-40

LIC
RTO
RIC
LTO
LIC
RTO
LIC
RTO
LIC
RTO
LIC
RTO

Quads
Gluteus
Gas-Soleus

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## Upper Limb Kinematics

### Reach & Grasp Cycle

#### Upper Limb Kinematics

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk Flexion/Extension</td>
<td>Trunk Axial Rotation</td>
<td>Shoulder Rotation</td>
<td>Shoulder Elbow</td>
<td>Elbow Flexion/Extension</td>
<td>Forearm Pronation/Supination</td>
<td>Wrist Flexion/Extension</td>
<td>Wrist Deviation</td>
</tr>
</tbody>
</table>

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**Legend:**
- **TD Mean ± 1 SD**
- **Spastic Hemiplegia CP 1**
- **Spastic Hemiplegia CP 2**

**Source:** JRose, Stanford University
Thank You

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