MOTOR CONTROL OF THE SPINE IN ACUTE, RECURRENT AND CHRONIC LBP: IMPAIRMENTS, ADAPTATIONS, AND CLINICAL APPLICATIONS

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DELITO et al., JOSPT, 2012

Individual muscle systems
How is motor control modulated?

- Amplitude of muscle activity
- Timing of muscle activity
- Muscle co-contraction

Altered motion

WHY IS MOTOR CONTROL DIFFERENT IN INDIVIDUALS WITH LBP?

Pain-spasm-pain model

WHY IS MOTOR CONTROL DIFFERENT IN INDIVIDUALS WITH LBP?

Pain - adaptation model
Motor control and low back pain

ACUTE/SUB-ACUTE LBP

RECURRENT LBP

RECURRENT LBP

RECURRENT LBP

CHRONIC LBP

TIME

Delitto et al., JOSPT 2012

INDIVIDUAL MUSCLE SYSTEMS

INTEGRATED SPINAL CONTROL

Healthy, Young, Fit Lumbar Muscle

Psoas

Multifidus

Erector Spinae

L4-L5
Morphologic Changes With LBP

Cause and Progression?

Physiologic CSA:

- Multifidus
- Rectus Abdominis
- Longissimus Thoracic
- Iliocostalis Lumborum
- Ward et al, JBJS, 2009
- Delp et al, J Biomech, 2001

PCSA (cm$^2$) = Muscle Mass (g) x $\cos \theta$ x $\rho$ (g/cm$^3$) x Fiber Length (cm)

Morphologic Changes With LBP

Physiologic Cross Sectional Area (cm$^2$)

Increasing Excursion

Increasing Force

Ward et al, JBJS, 2009
Delp et al, J Biomech, 2001
Atrophy & Fat Replacement

When?
• Acute?
• Subacute?
• Chronic?

Where?
• Generalized?
• Unilateral or bilateral?
• 1 segment? 5 segments?

Why?
• Reflex inhibition?
• Deconditioning?
• Denervation?
• Aging?
• Surgical procedures?

Morphologic Changes With LBP

Acute unilateral LBP – mean symptom duration: 13 days
• Atrophy at painful side and segment
  • 31% reduced cross-sectional area (CSA) – unilateral

Acute unilateral radicular symptoms – no atrophy

3. Kim et al, J Kor Neurosurg, 2011

Morphologic Changes With LBP

Early Chronic Unilateral NSLBP (Ave: 3 months)
• Painful side and segment: 21% reduced CSA

Radicular Symptoms
• Duration: 5.4 mos – 6.3% unilateral atrophy

2. Kim et al, J Kor Neurosurg, 2011
Morphologic Changes With LBP

Chronic LBP - Fat infiltration common

Mengiardi et al, Radiol, 2006
Parkkola et al, Spine, 1993

Volumetric Measurements

Subjects: LBP = 14, Controls = 14
- unilateral LBP: iliac crest to PSIS
- mean duration: 7.7 yrs
- mean ODI: 14.9%

Image segmentation: L4 inferior endplate to S1 inferior endplate

Muscle Volume =
CSA x slice thickness (5 mm) x # slices

Beneck & Kulig, APM&R, 2012

L5-S1 Multifidus Volume

18.1% reduced, bilaterally

Beneck & Kulig, APM&R, 2012
L4 Multifidus Volume

N = 26

Beneck & Kulig, APM&R, 2012

S2-S3 Multifidus Volume

Beneck & Kulig, APM&R, 2012

L5-S1 Erector Spinae Volume

Beneck & Kulig, APM&R, 2012
Muscle Morphology And Back Pain

Sample Case and Control: Unilateral Low Back Pain
• Pain/injury cause of atrophy?
• Local multifidus atrophy?

Lumbar Multifidus
• Series of overlapping bands and fascicles
• Spanning 2-5 segments
• Attaching to each of the 5 lumbar vertebrae

Prospective Validation Study

Hodges et al, Spine, 2006
Prospective Validation Study

Atrophy of deep fibers?

Deep Fibers = Short Fibers

Hodges et al, Spine, 2006

Multifidus Atrophy Localized To Painful Region

Healthy: matched for age, size and activity

Low Back Pain

Back Extensor Fatigability

Low Endurance

- Associated with LBP$^{1-5}$
- A Risk Factor for LBP$^{6-8}$

Sorensen test: max holding time

2. Neurabinio, JOSH, 2002
4. Tsuboi, Appl/Physiol Occup Physiol, 1994
**Back Extensor Endurance**

**Sorensen Test Limitations**
- 37% stopped for reasons other than fatigue

**EMG fatigue testing**

![Power Spectral Analysis](image)

Ropponen et al, *JOSPT*, 2005

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**Median Frequency Slope**

The median frequencies are plotted over time. The slope is the best-fit line of the median frequencies.

![Graph](image)

Beneck et al, *Electromyogr Kinesiol*, 2013

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**30 Second Hold**

![Graph](image)

P=0.650

Beneck et al, *Electromyogr Kinesiol*, 2013
Results – Low Back Pain

Normalized Median Frequency Slope, Mean (SEM)

L4 Deep Multifidus
L4 Superficial Multifidus
L4 Lumbar Multifidus
T10 Thoracic Longissimus
L4 Lumbar Longissimus

Simple Contrasts

DM vs TES P=0.013
SM vs TES P=0.135
LES vs TES P=0.114

Main Effect, Time P=0.008
Interaction, Time x Muscle P=0.027

Beneck et al, J Electromyogr Kinesiol, 2013

Slope Change: Deep Multifidus

CLBP

Healthy

Curvilinear Behavior – High Demand

Feline Multifidus: Reflex Activation

Human Tibialis Anterior

Less Demand

High Intensity Stimulation

80% MVC

Beneck et al, J Electromyogr Kinesiol, 2013

**Explanation?**

**Rapid drop out of type II motor units in deep multifidus**

**Selective atrophy of fast fibers in persons with LBP**

1. Fidler, JMS, 1975
4. Rantanen, Spine, 1993

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**Activation**

**Delayed Activation (Timing)**

- Sudden load
- Load release
- Arm movements

1. Magnussen et al, Eur Spine J, 1996

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**Influence of Anticipation on Activation**

**Self-initiated**

- Rapid Arm Movements
  - Feedforward activation – deep fibers only
- Loading
  - Earlier activation
  - Feedforward activation – deep fibers only

1. Moseley & Hodges, Spine, 2002
Impaired Activation with Recurrent LBP

Rapid Arm Movements\textsuperscript{1}
- Onset time delayed (20 ms) only in deep fibers on side of LBP

Loading Response
- Anticipation did not result in earlier activation in patients with disc herniation\textsuperscript{2}
- Bilateral reduction in amplitudes in deep fibers prior to load release with unilateral LBP\textsuperscript{3}.

1. MacDonald et al., Pain, 2009
2. Leinonen et al., Spine, 2001
3. MacDonald et al., Spine, 2010

Physiologic PCSA: Abdominal Muscles

Global Muscle Co-Contraction

TRUNK STIFFNESS DUE TO CO-CONTRACTION FROM GLOBAL MUSCLES

Lee et al., J Electromyogr Kin, 2006
Granata et al., Hum Factors, 2004
• Co-contraction of global muscles increases compression
• Importance of recruitment of local muscles

Deep Abdominal Muscle Impairment Associated With LBP

Onset time delay in CLBP

• Shoulder movements
  • Transversus Abdominis: 61 - 165 ms
  • IO: 5 - 54 ms
  • EO: 9 – 36 ms
• Hip movements
  • Transversus Abdominis: 119 - 137 ms
  • IO: 8 - 38 ms
  • EO: 13 – 51 ms

Hodges et al, Spine, 1996
Hodges et al, J Spin Disord, 1998

Trans Abd / Int Obl: Biomechanical Effects
Tension through the Thoracolumbar Fascia

Tension increased segmental stiffness in flexion only

Fascial tension resisted flexion: 9.5 N (2.2 lbs). Fascial tension decreased extension resistance by ~ 6.6 N.

Forces and moments are a small percentage of those produced by the lumbar extensors ~ 2-3%.  
2. Gatton, J Biomech, 2010


Image complements of Jacek Cholewicki
Intra-Abdominal Pressure

- Created by contraction of abdominal muscles, diaphragm and pelvic floor muscles.
- Previously, believed to merely counteract the flexor moment of abdominal muscles.
- IAP substantially increased stability by unloading spine during all external moments, and exceeded the flexion moment generated by the abdominal muscles.¹
- Spinal stability was not altered by selective activation by either transversus abdominis or oblique muscles.²

¹ Stokes et al, Clin Biomech, 2010
² Stokes et al, Clin Biomech, 2011

Hollowing vs. Bracing

Response to sudden loading

- Bracing reduced trunk displacement.
- Hollowing did not reduce trunk displacement.

Vera-Garcia et al, J EMG & Kines, 2007

Gluteal Muscle Impairment with LBP

- Duration of Gmax activity diminished during flexion.¹
- Delayed gluteus maximus activation returning from flexion in LBP developers.²
- Hip extensor strength asymmetry in females associated with LBP³ or predicted LBP.⁴
- Gluteus maximus more fatigable with LBP.⁵

¹ Leinonen, APM&R, 2000
² Nelson-Wong, Clin Biomech, 2012
⁵ Kankaanpaa, APM&R, 1998
Lumbopelvic Landing Kinematics and EMG in Women with Contrasting Hip Strength

JOHN M. POPVICH JR. and KORNELIA KULIG
Division of Biomechanics and Physical Therapy, University of Southern California, Los Angeles, CA

- Healthy subjects subgrouped based on hip strength: strong vs. weak
  - Weak group – greater peak trunk side bending
  - Weak group – greater trunk muscle co-contraction

Source of Impaired Activation?

Static Load
- Mechanical stimulus to supraspinous ligament
- Multifidus activated with physiologic loads
- Longissimus not activated until exceeding physiologic loads

Cyclic Loading
- Depressed reflex response in feline model

Cyclic Loading
- Depressed reflex response in feline model

Disc and facet stimulation
- Electrical stimulation to right posterolateral disc
- Electrical activity recorded
  - Multifidus bilaterally
  - Right > left
- Right longissimus only

Saline injection into facet reduced multifidus activity

2. Solomonow et al, Clin Biomech, 2000

Indahl et al, Spine, 1995
Indahl et al, Spine, 1997
Recurrent / Chronic Low Back Pain Cycle

- Reduced Neural Drive
- Atrophy
- ↓ Rate of Force Generation
- ↓ Strength
- ↑ Fatigability
- ↓ Intervertebral Stiffness
- ↓ Pelvic Control
- ↑ Susceptibility to Injury

Source Of Impaired Activation?

Cortical Inhibition?
- Porcine Model – Acute Injury
  - MEPs (cortical motor-evoked potentials) recorded in deep and superficial multifidis at L3-5 at side of IV disc lesion.
  - MEP amplitudes increased (36%), not decreased on the side of the disc lesion.
  - Increased corticomotor excitability suggests a compensatory response to reduced excitability at the spinal cord.
- Reduced cortical excitability in humans with chronic low back pain

2. Strutton et al, J Spin Disord & Tech, 2005

Source Of Impaired Activation?

Cortical Changes?
- Using TMS mapping, fascicles of multifidus and erector spinae are controlled by discrete neuronal regions within the motor cortex
- Loss of discrete organization of lumbar extensors in persons with recurrent LBP

How do we assess integrated spinal motor control?

1) Forward flexion
   - Voluntary control
   - Through-range spinal motion

   - Lumbopelvic rhythm
   - Aberrant motion
**Spinal motor control and LBP**

Zelka et al., *J Physiol*, 1999

Neumann, 2010
Spinal motor control and LBP

RECURRENT LBP

How do we assess integrated spinal motor control?

3) Locomotion

• Multi-planar postural control
• Mid-range spinal motion

Paraspinal muscle activity
Inter-segmental coordination
• In-phase
• Anti-phase

Inter-segmental coordination variability

Inter-segmental coordination

Pelvis rotation (degrees)

Trunk rotation (degrees)
Inter-segmental coordination variability

Spinal motor control and LBP

ACUTE/SUB-ACUTE LBP

CHRONIC LBP

Arendt-Nielsen et al., Pain, 1996
Vogt et al., Man Ther, 2003
Van der Hulst et al., / Electromyogr Kinesiol, 2010
**CHRONIC LBP**

- No consistent difference in single-joint kinematics
- Maintain in-phase coordination as speed increases\(^1,2,3\)
- Decreased inter-subject variability of inter-segmental coordination\(^2,3\)

1. Huang et al., *Eur Spine J*, 2010
2. Lamoth et al., *Eur Spine J*, 2006
3. Sales et al., *Clin Biomech* 2001

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**Spinal motor control and LBP**

**RECURRENT LBP**

- Young participants with at least 1 year history of recurrent LBP/matched controls
- Asymptomatic
- Walking turn
- Two speeds

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**Spinal motor control and LBP**

**RECURRENT LBP**

Baseline group comparison
- No difference in inter-segmental coordination
- No difference in inter-segmental coordination variability
- No difference in muscle activity
- *Altered modulation of muscle activity in response to faster walking condition*
Spinal motor control and LBP

Biomechanical effects of altered motor control

Changes in motor control with back pain
- Some dependent upon task/individual
- Some similar trends seen across tasks
- Reduced selectivity of muscle activity
- Greater superficial muscle activity
- Greater co-contraction
- "Guarded" movement
- Reduced movement variability

SENSORY/PERCEPTUAL AND COGNITIVE PROCESSES

ACUTE/SUB-ACUTE LBP

CHRONIC LBP

Effects of:
- Anticipation of back pain
- Fear avoidance
- Diffuse impairments in body perception
- Diffuse impairments in sensory processing
- Changes in cortical representation

1. Moseley et al., Pain, 2004
3. Ward et al., Man Ther, 2011
Biomechanical effects of altered motor control

Increased co-contraction
• Increased spinal stiffness

Biomechanical effects of altered motor control

Increased co-contraction
• Increased spinal load\(^1\)
• Impaired postural control\(^2,3\)
• Decreased damping\(^4\)

INDIVIDUAL MUSCLE SYSTEMS

INTEGRATED SPINAL CONTROL

CLINICAL APPLICATION
Clinical application

How do we assess?
- muscle morphology?
- muscle activation timing?
- muscle fatigue?
- co-contraction?
- altered coordination?
- altered variability?

What is the symptom response to changing movement patterns?

Clinical presentation of LBP

Which individuals have these problems?
- potentially all sub-groups
- substantial individual variability
- equivocal findings for relationship between motor control impairments and current classification systems
- acute/sub-acute/chronic low back pain with movement coordination impairments

Fritz et al., JOSPT 2007
Kiesel et al., JOSPT 2007
Silfies et al., J Orthop Sports Phys Ther 2009
Zielinski et al., Arch Phys Med Rehabil 2013
Delitto et al., JOSPT 2012

“E.P.”
Recreational cyclist
- 24 year old female
- 8 year history
- Bilateral low back pain
- Recurrent episodes
- Chronic discomfort
- Exacerbation due to cycling

Armour Smith, Poppert & Kulig, unpublished data
“E.P.”
Recreational cyclist

- Hypermobile
- SLR > 90 degrees
- Equivocal prone instability test
- L4 and L5 PAs painful

Armour Smith, Poppert & Kulig, unpublished data

“E.P.”
Recreational cyclist

Armour Smith, Poppert & Kulig, unpublished data

“E.P.”
Recreational cyclist

Extension phase

Armour Smith, Poppert & Kulig, unpublished data
"E.P." Recreational cyclist

Armour, Smith, Poppert & Kulig, unpublished data

Pelvis rotation (degrees)

Trunk rotation (degrees)

Coordination variability (angular deviation, degrees)

Armour, Smith, Poppert & Kulig, unpublished data

Recreational cyclist
IS MOTOR CONTROL INTERVENTION EFFECTIVE?

“E.P.”
Recreational cyclist

- 12 week progressive intervention
- Motor learning and strengthening
- Trunk and lower extremity musculature

Kulig et al., Phys Ther 2009
Flanagan, Kulig & PTCLINRESNET, JOSPT, 2010

Multifidus

Transversus Abdominis

- Quadruped progression
- Abdominal progression
• Squat/lunge progression

• Modified paraspinal progression

"E.P." Recreational cyclist

Sitting 5 minutes

Standing 5 minutes

No pain

Worst pain imaginable

Armour Smith, Poppert & Kulig, unpublished data

"E.P." Recreational cyclist

Armour Smith, Poppert & Kulig, unpublished data
Coordination variability
(angular deviation, degrees)

0%
20%
40%
60%
80%
100%

Stride cycle

Armour, Smith, Ruppert & Kulig, unpublished data

HOW CAN WE MODIFY TRUNK MOTOR CONTROL?

Manual techniques
Exercise interventions
Motor (re)learning

Extensor Activation Post Manipulation (sEMG)

• EMG amplitude decreased\(^1\)
• EMG amplitude diminished at painful segment only after manipulation\(^2\)
• Increase in sEMG amplitude during MVIC after manipulation\(^3\)

1. DeVocht, JMPT, 2005
2. Lehman, JMPT, 2001
Multifidus Post Manipulation Activation

- On average, total group (N=81) had greater activation at L4-5 at 3-4 days.
- MF increase in thickness explained only 7% of variance in ODI score.
- Responders (≥30% ODI reduction) experienced significantly more activation at 3-4 days, but not immediately or 1 week later.


Abdominal Activation Post Manipulation

- Feedforward activation improved post-manipulation in healthy individuals with delay\(^1\)
- Case series meeting manipulation CPR – 6 of 9 patients increased TrA muscle thickness during ADIM post-manipulation\(^2\)
- Rapid shoulder flexion – persons with LBP (not control group) exhibited higher amplitudes in both IO and EO (fine-wire EMG)\(^3\). TrA and RA: no change.

1. Marshall, JMPT, 2006
2. Ranney, JOSPT, 2007
3. Ferreira, Man Ther, 2007
Abdominal Activation Post Manipulation
N=81, met and did not meet manipulation CPR
• TrA thickness change decreased immediately post SMT during ADIM.
• IO thickness change decreased immediately post SMT during ASLR.
• No change 1 week post SMT.
• No change in those who improved from manipulation.

Case series – met stabilization CPR: “No significant differences in resting, contracted, or percent thickness change in the TrA or IO were found over the 3 time periods.”

1. Koppenhaver, JOSPT, 2011
2. Konitzer, JOSPT, 2011

Multifidus Atrophy Localized To Painful Region

Healthy: matched for age, size and activity
Low Back Pain

Training with Postural Cuing

Short Lordosis
• Verbal Cue: “Push your tailbone up over your head”

Palpatory and verbal feedback

*Short lordosis – Claus et al, Spine, 2009
Activation with Postural Cuing: Kneeling Side Plank

Postural Cuing Activation With Exercise

1. Contralateral Arm/Leg Extension
2. Side Plank on Knees
3. Prone Leg Lift
4. Prone Trunk Extension
5. Roman Chair 15°
6. Roman Chair 45°
Is motor control intervention effective?

Does isolated muscle training affect timing of postural activation in short and long term?
- Isolated muscle training may help to redistribute muscle activation or effect muscle timing
- Isolated muscle training may affect motor cortical spatial representation

Tsao et al., J Electromyogr Kinesiol, 2008
Tsai et al., Spine, 2012
Tsao et al., J Park, 2010

Is motor control intervention effective?

Motor skill training (versus general exercise) can alter corticospinal excitability and cortical representation
Strength training increases excitability, but skill training alters representation

Boudreau et al., Man Ther, 2010
Adkins et al., J Appl Physiol, 2006
Fisher et al., JOSPT, 2013

Is motor control intervention effective?

- Task-specific training may alter coordination and movement patterns
- Movement re-education may reduce symptoms

1. Hoffman et al., Man Ther, 2012
2. Van Dillen et al., Man Ther, 2009
Intervention

Recognize individual adaptations to pain
Maximize neuroplasticity
• Motor skill training
• Cognitive effort
• Quality not quantity of repetition
• Modulate complexity of task and environment

Framework for intervention

Framework for intervention
How is motor control altered by pain?

- Some consistent adaptations across individuals
- Some inconsistent adaptations between individuals

Why is motor control different in individuals with LBP?

Adaptation specific to muscle, task, and individual
Complex due to complexity and redundancy of trunk muscle system

- Musculoskeletal system ✓
- Central nervous system ✓
- Sensory/perceptual processes ✓
- Cognitive processes ✓


