Motor Control of the Spine in Acute, Recurrent and Chronic LBP: Impairments, Adaptations, and Clinical Applications

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What is motor control?

- The production of coordinated movement
- Interaction between the individual, task and environment
- Multiple systems and processes

Shumway-Cook & Woollacott, 2007
What is motor control?

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

Individual muscle systems

How may motor control be altered?

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

Altered motion
How may motor control be altered?

- Adaptability = variability
- Some variability is associated with stable performance of a task
- Allows individual to achieve task under changing environmental conditions and task constraints
- Altered variability is associated with ageing and some musculoskeletal disorders

How may motor control be adapted?

- Some consistent adaptations across individuals
- Some inconsistent adaptations between individuals
- Complex due to redundancy of trunk muscle system

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

L3-L4
L4-L5
L5
L5-S1

Physiologic PCSA: Multifidus

Ward et al, AIRS, 2009
Delp et al, J Biomech, 2001
Length-Tension Curve: Multifidus

Morphologic Changes with LBP

Cause and Progression?
Atrophy & Fat Replacement

- When?
  - Acute?
  - Subacute?
  - Chronic?
- Where?
  - Generalized?
  - Unilateral or bilateral?
  - 1 segments? 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

Morphologic Changes with LBP

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

Hides et al, Spine, 1994
Ultrasound Images
Hides et al, JOSPT, 2008

Barker et al, Spine, 2004
Morphologic Changes with LBP

Chronic LBP - Fat infiltration common

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

Volumetric Measurements

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

*P = 0.026

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

N = 26


S2-S3 Multifidus Volume


L5-S1 Erector Spinae Volume

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?

Campbell et al, Muscle & Nerve, 1998
Kader et al, Clin Radol, 2000
Hodges et al, Spine, 2006

Deep Fibers = Short Fibers

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. Nourjah, JOSPT, 2002
4. Tsubo, Appl Physiol Occup Physiol, 1994

Back Extensor Endurance

• Sorensen Test Limitations
  – 37% stopped for reasons other than fatigue^1
• EMG fatigue testing

MF Slope

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

P=0.650

Normalized Median Frequency Slope, Mean (SEM)

Deep Multifidus
Superficial Multifidus
Lumbar Longissimus
Thoracic Longissimus

Beneck et al, J Electromyogr Kinesiol, 2013

Results – Low Back Pain

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

Beneck et al, J Electromyogr Kinesiol, 2013
**Curvilinear Behavior – High Demand**

- Feline Multifidus: Reflex Activation
  - High Intensity Stimulation
  - 80% MVC

- Human Tibialis Anterior
  - 80% MVC

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**Explanation?**

- Rapid drop out of type II motor units in deep multifidus
- Selective atrophy of fast fibers in persons with LBP

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**Activation**

- Delayed Activation (Timing)
  - Sudden load
  - Load release
  - Arm movements

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Source references are indicated at the bottom of each section.
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**
  - 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
  - Bilateral reduction in amplitudes in deep fibers prior to load release with unilateral LBP

1. MacDonald et al, Pain, 2009

Physiologic PCSA: Psoas

- Increasing Excursion
- Increasing Force

Regev et al, Spine, 2011
Psoas (PS) & Quad Lumb (QL) Atrophy

- Mixed findings
  - Atrophy
    - Unilateral LBP (3 mos duration): 12.3%\(^1\)
    - Unilateral LBP, most radicular (3 mos duration)\(^2\): PS: 7.7-17.1%; QL: 13.9-24.8%
    - LBP > 1 year duration\(^3\): PS: 13.2%; QL: 13.2%
  - No atrophy
    - Professional dancers\(^4\): PS & QL
    - Unilateral sciatica\(^5\)
  - Hypertrophy
    - Chronic nonradicular LBP\(^6\)

1. Barker, Spine, 2004
2. Ploumis, Br J Radiol, 2011
5. Kim, Kor Neurosurg Soc, 2011
6. Arbanas, Eur Spine J, 2013

Psoas Activation with LBP

- Spinal curvature changes
  - Psoas major and QL signal amplitude similar to controls.
  - Subgrouping: high and low ES EMG activity
    - Psoas high when ES low
    - Psoas low when ES high

Park, JFK, 2013
Abdominal Muscle PCSA


Physiologic Cross-Sectional Area (cm²)

<table>
<thead>
<tr>
<th>Fiber Length (cm)</th>
<th>Rectus Abdominis</th>
<th>Transversus Abdominis</th>
<th>External Oblique</th>
<th>Internal Oblique</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>&lt; 2</td>
<td>&lt; 4</td>
<td>&lt; 6</td>
<td>&lt; 6</td>
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<tr>
<td>5</td>
<td>&lt; 2</td>
<td>&lt; 4</td>
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<tr>
<td>30</td>
<td>&lt; 2</td>
<td>&lt; 4</td>
<td>&lt; 6</td>
<td>&lt; 6</td>
</tr>
</tbody>
</table>

Increasing Excursion

Increasing Force

Global Muscle Co-Contraction

Trunk stiffness due to co-contraction from global muscles

Lee et al., *Electromyogr Kin*, 2005
Granata et al, *Hum Factors*, 2004

- Co-contraction of global muscles increases compression
- Importance of recruitment of local muscles

Image complements of Jacek Cholewicki
Transversus Abdominis

Does not flex the spine or posteriorly tilt the pelvis.
- Biomechanical effects:
  - Resist motion?
  - Increase in IAP?

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 Spinal Disord, 1998

Transversus Abdominis / IO: 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
3. MacIntosh, Clin Biomech, 1987
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 unloaded spine in all directions of 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

Physiologic PCSA: Gluteal Muscles

Ward, CORR, 2009
Gluteal Muscle Impairment with LBP

- Duration of Gmax activity diminished during flexion\(^1\)
- Delayed gluteus maximus activation returning from flexion in LBP developers\(^2\)
- Delayed gluteus medius activation during stork stand with SIJ pain\(^3\)
- Hip extensor strength asymmetry in females associated with LBP\(^4\) or predicted LBP\(^5\)
- Gluteus maximus more fatigable with LBP\(^6\)

1. Leinonen, AJMBA, 2000

Lumbopelvic Landing Kinematics and EMG in Women with Contrasting Hip Strength

John M. Popovich Jr. and Kornelia Kulig
Division of Biokinesiology and Physical Therapy, University of Southern California, Los Angeles, CA


Biomechanical Consequences of Gluteal Muscle Weakness

"simulated facet loading increased during simulated pelvic obliquity"
Source of Impaired Motor Control?

- **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

Source of Impaired Activation?

- 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

Recurrent / Chronic Low Back Pain Cycle

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

• Cortical Inhibition?
  – Porcine Model – Acute Injury
    • MEPs (cortical motor-evoked potentials) recorded in deep and superficial multifidus 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 Spine 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) Postural perturbations

• Anticipated/unanticipated
• Postural control
• Mid-range spinal motion
Spinal motor control and LBP

**ACUTE/SUB-ACUTE LBP**

<table>
<thead>
<tr>
<th>Reaction time (ms)</th>
<th>Deltoid</th>
<th>Trunk</th>
<th>Deep MF</th>
<th>OI</th>
<th>OE</th>
<th>Sup MF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>180±14</td>
<td>154±15</td>
<td>17±14</td>
<td>18±16</td>
<td>220±37</td>
<td>18±11</td>
</tr>
<tr>
<td>Attention</td>
<td>20±6±10</td>
<td>16±4±21</td>
<td>19±5±26</td>
<td>20±5±30</td>
<td>320±46*</td>
<td>28±17±10</td>
</tr>
<tr>
<td>Stress</td>
<td>28±6±20*</td>
<td>27±6±20*</td>
<td>28±6±20*</td>
<td>28±6±20*</td>
<td>32±6±20*</td>
<td>28±6±20*</td>
</tr>
<tr>
<td>Pain</td>
<td>187±19</td>
<td>18±16</td>
<td>18±16</td>
<td>16±16</td>
<td>21±16</td>
<td>18±16</td>
</tr>
</tbody>
</table>

*Significant difference from control (P<0.01)

**CHRONIC LBP**

- Task-specific changes in co-contraction
Spinal motor control and LBP

CHRONIC LBP

- Reduced center of pressure displacement
- Increased center of mass displacement
- Reduced preparatory spinal motion
- Increased resultant spinal motion

1. Henry et al., Clin Biomech, 2006

Spinal motor control and LBP

CHRONIC LBP

How do we assess integrated spinal motor control?

2) Forward flexion

- Voluntary control
- Through-range spinal motion

1. Jacobs et al., Behav Neurosci, 2009
• Lumbopelvic rhythm
• Aberrant motion

Spinal motor control and LBP

ACUTE/SUB-ACUTE LBP

Zedda et al., J Physiol, 1999

Spinal motor control and LBP

RECURRENT LBP

Esola et al., Spine, 1996
McClure et al., Spine, 1997
Spinal motor control and LBP

CHRONIC LBP

Flexion phase

Extension phase

Paraspinals

Gluteus maximus

Biceps femoris

How do we assess integrated spinal motor control?

3) Locomotion

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

- Steady-state locomotion
- Perturbed locomotion
Steady state locomotion

Perturbed locomotion

Pelvis rotation (degrees)
Trunk rotation (degrees)

Pelvis displacement (degrees)
Trunk displacement (degrees)

Pelvis angular displacement (degrees)
Trunk angular displacement (degrees)
Spinal motor control and LBP

ACUTE/SUB-ACUTE LBP

Control condition  Pain condition

Lamoth et al., Clin Biomech, 2004

Spinal motor control and LBP

Pain condition

Control condition

Seay et al., Spine, 2004

Spinal motor control and LBP

RECURRENT LBP

Change in coordination pattern (% of swing phase)

Armour Smith & Kulig, unpublished data

Armour Smith & Kulig, unpublished data

Spinal motor control and LBP

RECURRENT LBP

Change in duration of multifidus activation (% of stride cycle)

Armour Smith & Kulig, unpublished data
Spinal motor control and LBP

**CHRONIC LBP**

Lamoth et al., *Eur Spine J*, 2006

**Healthy**

**LBP**

Arendt-Nielsen et al., *Pain*, 1996

Healthy LBP

CHRONIC LBP

Vogt et al., *Man Ther*, 2003

Thoracic paraspinals

Lumbar paraspinals

Gluteus Maximus

Rectus Femoris

Thoracic paraspinals

Lumbar paraspinals

Gluteus Maximus

Rectus Femoris
Biomechanical effects of altered motor control

Assumption
• Some motor control changes are maladaptive and should be modified

Reality? It depends……
• Acute versus chronic situation
• Individual patterns of adaptation

Biomechanical effects of altered motor control

Increased co-contraction
• Increased spinal stiffness

Increased co-contraction
• Increased spinal stiffness
Biomechanical effects of altered motor control

Increased co-contraction
- Increased spinal load
- Impaired postural control
- Decreased damping

Clinical application

Can we assess
- muscle morphology?
- muscle activation timing?
- co-contraction
- altered coordination?
- altered variability?
- 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
Case study

**“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

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**“E.P.”**
Recreational cyclist

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

Armour Smith, Poppert & Kulig, unpublished data

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**“E.P.”**
Recreational cyclist

![Graphs of Lumbar and Thoracic paraspinals](Armour Smith, Poppert & Kulig, unpublished data)

- Flexion
- Extension
“E.P.”
Recreational cyclist

Extension phase

Lumbar spine angle (degrees)

Hip angle (degrees)

Armour, Smith, Poppert & Kulig, unpublished data

“E.P.”
Recreational cyclist

Stride cycle

Amplitude

Armour, Smith, Poppert & Kulig, unpublished data

“E.P.”
Recreational cyclist

Pelvis rotation (degrees)

Armour, Smith, Poppert & Kulig, unpublished data
Cause or effect?

![Diagram](image)

**Transient LBP model**
- Pain developers have greater flexor/extensor and gluteal co-contraction
  
- On extension from flexion, pain developers have delayed gluteal activation relative to paraspinal activation

1. Nelson-Wong et al., J Electromyogr Kines, 2010

**Prospective study – collegiate athletes**
- Delayed muscle offset latencies were predictive of future back injuries
- But is this specific to the trunk or just reflective of generally poor reaction times?

1. Cholewicki et al., Spine, 2005
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

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 ✓
Sensory/perceptual and cognitive processes

**CHRONIC LBP**

Effects of:
- Anticipation of back pain
- Fear avoidance
- Diffuse impairments in body perception
- Diffuse impairments in sensory processing
- Altered cognitive control of motor activities

1. Moseley et al., Brain, 2004
3. Wand et al., J Phys Ther, 2011

Sensory/perceptual and cognitive processes

**ACUTE/SUB-ACUTE LBP**

- Delay in APA onset and reduction in variability of APA onset prolonged in some healthy subjects
- Associated with pain beliefs
- Altered cognitive control of locomotion in persons with CLBP

1. Moseley & Hedges, J Neurol Neurosurg, 2006
2. Lassen et al., NeuroEngineering Rehab, 2008

How do 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 - US

- 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.

Multifidus Post Manipulation
Activation - US

- Variables together resulted in an adjusted $R^2$ of 0.27 - change in LM thickness 1 week post-manipulation.
  1. Acute LBP
  2. Moderately good prognosis without focal and irritable symptoms
  3. Signs of spinal instability

Abdominal Activation Post Manipulation

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

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."

References:
1. Koppenhaver, JOSPT, 2011
2. Kosinski, JOSPT, 2011
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
• Isolated muscle training may affect motor cortical spatial representation

Tsao et al., J Electromyogr Kinesiol, 2008
Vasikaran et al., Spine, 2012
Tsao et al., J Pain, 2010
Tsao et al., Eur J Pain, 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

Intervention

• Multi-modal intervention may improve timing of gluteus maximus activation
• Trunk/hip strengthening intervention reduced pain but had variable outcome on co-contraction during prolonged standing
• Task-specific training may alter coordination and movement patterns
• Movement re-education may reduce symptoms

1. Lennonon et al., Arch Phys Med Rehabil, 2000
2. Nelson Weng et al., J Electromyogr Kinesiol, 2010
3. Hoffman et al., Man Ther, 2012
4. Van Oelen et al., Man Ther, 2009
Multifidus Atrophy Localized to Painful Region - Postural Cuing

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”
- Unilateral activation
  - Short lordosis cue
  - “Swing your tailbone to the right”
- Palpatory feedback

Postural Cuing Activation Lower Lumbar

- Multifidus
- Longissimus Thoracic
Postural Cuing Activation
Kneeling Side Bridge

Exercises
1. CONTRALATERAL ARM/LEG EXT
2. SIDE PLANK ON KNEES
3. PRONE LEG LIFT
4. PRONE TRUNK EXTENSION
5. VARC 45°
6. VARC 15°

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
Is motor control intervention effective?

- 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

Flexion Extension

Lumbar paraspinals
Thoracic paraspinals

Armour Smith, Poppert & Kulig, unpublished data

“E.P.”
Recreational cyclist

Pre-intervention
Post-intervention

Armour Smith, Poppert & Kulig, unpublished data
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

CONTROL

context

complexity

cognition
Selected References