Prevention of Spinal Injury from Excessive Loading: Biomechanical Rationale
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Rational Lumbar Spine Rehabilitation Based on Spinal Mechanics
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Why Don’t We Know
- A System of Articulations
- Circumferential Muscular Attachments
- Multiple Degrees of Freedom
- Locomotion/Movement/Support
- Only Functional in Living Subjects
- Complex interactions
- Inaccessible
Two Basic Functions

- Stability - Loading and Support
- Mobility - Locomotion and Movement

Man is the only animal with lordosis in the lumbar spine; enabling work and portage

History of Clinical Spinal Biomechanics through 1960's

- Mixter and Barr (1932) - HNP of the lumbar disc as the focal point of spinal pathology
- Hirsch and Nachemson (1951) - Biomechanical Analysis of Compressive Disc injury

Floyd and Silver (1951)

- Correlated Workplace Lifting with Disc Injury
- Applied Biomechanical Principles to Lifting
- Increased Lever Arm Multiplies Effective Load
- Muscles not strong enough to lift loads that were being lifted
Floyd and Silver (1955)

Flexion-Relaxation Phenomenon (FRP)

- EMG silence as trunk goes from fully erect standing position to fully flexed

- Lumbar Muscles Not Contracting?

- What is Supporting the Trunk?

Bartelink (1957)

- Combined Compressive Force of: (Load) + (Extensor Muscle Force) x Fulcrum of Trunk = Approximately 1500kg Load

- "Compression to Failure of Disc"= 750kg

- Loads Exceed Force Capacity of Muscles

- Forces Exceed Compression Strength of Disc

British Medical Association Address

PR Davis (1959)

- Many ways to lift, but for relevant objects workers did ‘bent back’ (stoop) or ‘straight back’ (squat)

- The larger the load, the straighter the spine

- Passive Ligaments must support spine during Flexion

- Intra-abdominal pressure protects the spine from compressive injury
The Three Unanswered Questions

- Are the back muscles strong enough to lift the amount of weight being observed?
- Can the discs support the compressive forces exerted on them?
- Do back muscles relax during flexion?

Early in vitro Lumbar Spine Bench Testing Demonstrated Endplate Failure

- Compression of Intervertebral disc results in endplate fracture (Thornton Brown, 1957)
- Compression failure of spine occurs through endplate at 750kg (Bartelink 1957)
- Pure compression yields endplate fractures, not disc failure (Rolander, 1975)

In vivo Findings Verified Experimental Data: Loads and Muscle Forces High

- Nachemson and Hirsch (1960)
Origins of Spinal Load Bearing Science: White and Panjabi 1971

- Coupled Motion- Flexion/Compression; Lateral Bending/Rotation; Extension/Distraction
- The “Neutral Zone”- No ligamentous support between the extremes of movement
- Preload- Muscle force and trunk mass tension ligaments and compress joints

Evolution of Spinal Biomechanics: Preload During Bench Tests

- Spinal segments without preload fail within physiologic range of loading
- Preloads applied along total spinal mechanical axis
- Preload applied along lordotic curve of lumbar spine

“In Lordosis the Spine can Withstand the Observed Loads”

Mechanical Bench Testing with Physiologic Preloads

- Preloaded Compression occurs through Posterior Annulus (Panjabi, 1977)
- Flexion/Compression creates annulus tension and posterolateral rupture (Adams 1982)
- In extension, with facet loading, the spine can resist large loads (Shiraz-Adl, 1984)
- Load carrying capacity of lumbar spine increased sharply under conditions of a follower load (Patwardhan, 1999; Rohlmann, 2001)
One Unanswered Question Addressed:

• The lumbar spine can withstand the observed forces imposed on it, if the preload maintains the spine in lordosis.
• The load is shared by the facets and posterior annulus.

Computational Models of Lifting to Predict Muscle Forces and Spinal Loads

1) Single Vertebral Level
2) Lumbar Spine Only
   1) Static (Equilibrium)
   2) Dynamic
3) Lumbar spine and lower extremities
   1) Static (Equilibrium)
   2) Dynamic

EMG Assisted Estimation of Muscle Forces in Lifting

Calculate the Moment of the External Load
Measure the Axial compression within the disc space
Record the EMG Signal And estimate the Force of the Muscle
Static, Single Level with EMG-assisted Muscle Force Measurement

- Schultz (1982) Static Weight Hold, EMG, IAP, and measured intra-discal pressure
- Calculated Muscle Forces and Spinal Loads Through the Single L3-L4 Level, found:
  - Intra-Abdominal Forces Negligible
  - Lumbar Extensor Muscles Could Lift Observed Loads
  - Discal Pressures could quadruple w/ flexed spine under load

Two Unanswered Questions:

- Valid only for Motion of One Segment

- Disc pressures during flexion still exceed 2000 kPa which is near the tissue tolerance of the IVD

Kinematic Model of Total Lumbar Spine

Developed a Total Spinal Model that was valid for every level in the spine from T12 to S1; i.e. the muscles balanced at every segment in the spine (Arjmand, 2008)
Comparison Static Single-level to Total Spinal Kinematic Model (Arjmand, 2009)
- Single-level Model underestimated synergy of combined muscle forces
- Kinematic model predicts greater lifting force for global extensor muscles (wrapping)
- Disc loads still very high for loads away from body, 3,000 kPa

This Model Reproduces Lifting through Forward Flexion of the Spine
- Total Kinematic Spinal model reveals global extensor muscles can generate the necessary force for routine lifting tasks (45 lbs)
- The lifting motion was from spine flexed to spine extended
- The loads on the L5-S1 disc remain near the maximum load limits of the tissue

History of Clinical Spinal Biomechanics: Whole Body Lifting Mechanics

<table>
<thead>
<tr>
<th>Stooped Lifting Posture</th>
<th>Squat Lifting Posture</th>
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<tbody>
<tr>
<td>Spine Flexed</td>
<td>Spine Flat (Lordotic)</td>
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<tr>
<td>Knees Straight</td>
<td>Knees Bent</td>
</tr>
<tr>
<td>Trunk Horizontal</td>
<td>Trunk Vertical</td>
</tr>
<tr>
<td>Arms Extended</td>
<td>Arms Close to Trunk</td>
</tr>
<tr>
<td>Long Moment Arm</td>
<td>Shorter Moment Arm</td>
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</table>
The Stooped Lift Posture

Advantages
- Can reach loads further away
- Requires less energy
- Lumbar muscles not active
- Passive ligamentous support
- May involve IAP
- Large Forces on L5/S1 Disc

Provides Mobility to Lifting

The Squat Lift Posture

Advantages
- Lumbar Spine held in Lordosis and able to withstand high loads
- Involves lower extremity muscles in lifting force production
- Reduction of moment arm applied to trunk

Contribution of Lower Extremity Muscles to Squat Lift(Seonhong, 2009)
- The hip extensors create twice the lifting force of the lumbar extensor muscles
- The lumbar extensors just maintain lordosis
- The role of the lumbar extensors is "not to lengthen"
The Rigid Spine is Extended by the Rotating Pelvis

Pelvic Rotation Extends Spine

Kinematic Model Applied to Dynamic Squat vs Stoop Lift (Bazgari, 2007)

Stoop Lift (Flexed Spine)  Squat Lift (Lordotic Spine)
- Spinal Extension provides weak lifting force
- High Intradiscal Pressure
- Increased mobility
- Lower energy expenditure for equivalent tasks

The Hip and Thigh muscles double the lifting force
Lower Intradiscal Pressure
Spine in Lordosis; Arms held in
Disks are under lower compressive force

Checks and Balances

The Relatively Weak CONCENTRIC Strength of the Lumbar Extensor Muscles Prevent them from Exposing the Lumbar Spine to Loads that could injure the Discs

The Relatively Strong ECCENTRIC Property of the Lumbar Extensor Muscles Keep the Spine from Flexing and Subjecting the Discs to Dangerous Loads
Recipe for Injury

- Hip and Thigh muscles lift weight
- Load exceeds eccentric strength of extensors
- Lumbar spine falls into flexion
- Disc compressive force exceed tolerances
- Annulus failure and Herniation

Role of Muscles in Lumbar Spine Stability in Maximum Extension Efforts (Gardner-Morse, 1995)

- Maintenance of Extension= “Active Stiffness”
- Activated Muscles Behave as “Stabilizing Springs”
- Not “Force Generators”

Biomechanical Analysis of Eccentric Lifting Exertions (Shu, 2011)

- Excessive Load Compels Lumbar Muscles to Lengthen
- Eccentric Forces Induced Significantly Higher Spinal Compression Forces \( (p<0.05) \)
- EMG Silence During Eccentrics
  - EMG during eccentric muscle lengthening is lower than concentric at same load (Komi, 2000)
  - Concentric EMG greater than Eccentric EMG; Fivefold increase with fatigue (Tesch, 2000)

The Passive Eccentric Force of Lengthening Physiologically Replicates the “Flexion-Relaxation Phenomenon”
Excessive Load Compels Lumbar Muscles to Lengthen

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The Passive Eccentric Force of Lengthening Physiologically Replicates the “Flexion-Relaxation Phenomenon”

Maintain Lordosis; Protect the Spine!

- Extensors don’t need to extend the spine but rather prevent the spine from being forced into flexion
- Eccentrically Train Lumbar Extensor Muscles
- The ‘Flexion Relaxation Phenomenon’ is Eccentric Lengthening of the Extensors
Origins of the Spinal Movement Perspective: Farfan 1971

• Torsion creates outer annulus tears as opposed to compression
• Autopsy Study showing outer annulus injuries in discs
• Biomechanical studies showed the L3-4 disc with outer annulus failure
• Findings challenged because of absence of no muscular forces creating torsion

Origins of Spinal Movement Perspective: Gracovetsky (1977)

• Nuclear Physicist applied principles of mathematical modeling to spinal movement
• Developed theory of human locomotion with spine as “prime mover”; limbs secondary
• The “Abdominal Mechanism” as the source of power for locomotion


• Theory of spinal extension for lifting through abdominal musculature activation
• The insertion of the Transversus Abdominis on the deep lumbodorsal fascia
• Secondarily the role of intra-abdominal pressure in spinal stability
• “Unified Theory” of spinal function (locomotion and stability)
Unified Theory Applied to Lifting

- Stooped Lift engages posterior ligaments: Flexion Relaxation=Transfer load to ligaments
- Abdominal muscle activation tensions the lumbodorsal fascia
- Intra-abdominal pressure helps lift loads and protects discs from compressive injury

Spinal Movement Theory 1: Do Posterior Spinal Ligaments Create Lift Force?

- Incidence and Force Inadequate to create Extension Moment (MacIntosh, 1987)
- Biomechanical Testing of Cadaveric Specimens show no extension moment (McGill, 1988)
- Kinematic Driven Biomechanical Analysis of Global Lumbar Lifting shows no Transversus Abdominis contribution (Arjmond, 2009)
Spinal Movement Theory 3:
Does IAP Create Extension Force?
- IAP is small and does not have a large influence on trunk mechanics (Schultz, 1982)
- Valsalva maneuver increased disc pressure during maximal lift (Nachemson, 1986)
- IAP is offset by the flexor moment created by the contracting muscles (Cholewicki, 2004)
- IAP is unrelated to the amount of isometric, extensor lift force (Hagins, 2010)

The Effect of Abdominal Tension on Spine Compression

Calculate the Moment of the External Load

Estimate the Flexion Force and Moment arm of Abdominal Muscles

Record the EMG Signal And estimate the Force of the Muscle

Kinematic Analysis of IAP (Arjmand, 2006)
- IAP Alone (9kPa) Reduces Spinal Compression by 19% in Flexion and Standing
- IAP + Abdominal Tension has No Reduction in Spinal Compression in Standing
- IAP + Abdominal Tension reduces Spinal Compression 7% in Flexion
- Large Data Scatter but IAP increases as Lumbar Flexion increases
Neurologic Mechanism for Transversus Abdominis (Hodges, 1996, 1997)

- Original studies postulated that the TrA contracts prior to limb movements to stabilize spine
- The deep trunk muscles don’t contribute much force but their “fine tuning” is essential for “optimal spinal health”.
- The CNS predicts mechanical events and can prepare the spine thru “feedforward control”
- 1/50 of second delay results in LBP

The Myth of Core Stability (Ledermann, 2010)

- Damage to abdominal musculature does not impair movement or contribute to LBP.
- Timing is beyond conscious control and the capability to clinically alter.
- Control is subconscious and requires interaction between all the synergistic muscles
- There is no support from research that TrA can be singularly activated

Emphasis on Abdominals vs. Extensors: What’s the Harm?

**Short Term**
- Occasional Abdominal Exercise is Benign
- Chronic Abdominal Focus to Exclusion of Extensor Strength, Potentially Harmful
- Wasteful Time, Money, and Resources

**Long Term**
- Discs have No Local Blood Supply for Nutrition
- Chronic Flexion Suppresses Disc Osmosis
Juvenile Discogenic Disease

- a.k.a. Type II Scheuermann's Disease
- Vertebral Growth Arrest
- Decreased Disc Height
- Premature Disc Degeneration
- Clear Loss of Normal Lordosis


Muscular Etiology of Senile Kyphosis

Chronic Posterior Muscular Insufficiency

Anterior Shift of Center of Gravity

Increased Discal Pressure

Loss of Disc Height

Further Kyphosis

Increased Vertebral Body Stress

Effect of Back Muscle Strength and Sagittal Spinal Imbalance on Locomotive Syndrome in Japanese Men

Kenichi Hirano, MD, Shiro Imaiga, MD, PhD; Yusuke Nomura, MD, PhD; Norimichi Waki, MD, PhD; Aki Misono, MD, PhD; Naoki Ishiguro, MD, PhD
The Future

- Elucidation of the "Flexion-Relaxation Phenomenon"
- "Motor Learning" Must Be Consistent with Biomechanical Principles
- Development of Training Strategies to emphasize Lordosis