Identification of Risk Factors for ACL Injury and Re-Injury: Implications for Prevention and Rehabilitation

2012 E.A.T.A. Convention

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Overview

• Prospective risk factors for ACL injury
  – JUMP-ACL study findings

• Potential risk factors for ACL re-injury
  – Same as incident ACL injury?

• Implications for ACL injury prevention and return to participation decision making
The ACL Injury Problem

• Disability:
  – 77% sports disability in 5 yrs
  – 44% disability with ADL’s in 5 yrs
  – Increase Risk of Knee Osteoarthritis
    • No Surgery: >90% in 20 years
    • “Good” Surgery: >90% in 20 years
How can we avoid ACL injury / re-injury?

3 Keys to Improving:

1. Understand risk factors for injury / re-injury
2. Systematic exercise progression
   - Focus on modifying risk factors
3. Systematic return to play criteria
   - Based on successful modification of risk factors
• 5 year trial at each academy
• 400 / academy / year
  – ~40% female
  – ~6,000 subjects
  – 15,000 man-years
• Goal = Capture primary ACL injuries
JUMP - ACL Research Team

UNC Chapel Hill
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- Barry Boden, MD (Ortho Cntr)
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- Brent Arnold / Scott Ross, PhD, ATC (VCU)

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- Greg Calhoon, ATC

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- John Tokish, MD
- Keith Odegard, MD

USMA
- Dean Taylor, MD
- Paul DeBeradino, MD
- Steve Slovoda, MD
- Kenneth Cameron, PhD, ATC
- Sally Mountcastle, PhD
- Jennifer Jones, Med, ATC
Jump-Landing Task

- Drop height = 30 cm
- Horizontal distance = 50% body height
- Jump for maximum vertical height immediately after landing
- Collected 3-D joint kinematics & kinetics
  - Electromagnetic system & force-plate
Strength Testing

Hip Extension
Hip Abduction
Hip External Rotation
Hip Internal Rotation
Knee Flexion
Knee Extension
Postural Alignment Testing

Q-Angle

Navicular Drop
Preliminary Findings: Males vs. Females

• Sex differences ≠ ACL injury risk factors
  – No differences in strength or postural alignment between injured and uninjured subjects
  – Sex differences in jump-landing biomechanics do not directly translate to ACL injury risk factors
## Key Findings

### Non-Contact / Indirect Contact
Primary ACL Injuries

<table>
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<td>n</td>
<td>Pct</td>
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<td>Females</td>
<td>2,395</td>
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<td>Males</td>
<td>3,631</td>
<td>61%</td>
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<tr>
<td>Total</td>
<td>6,026</td>
<td>100%</td>
<td>98</td>
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</table>
**Knee Flexion**
- No difference in knee flexion kinematics
- Both groups land with small knee flexion

**Knee Valgus**
- ACL injured land in valgus position
- No difference in peak knee valgus

**Knee Rotation**
- No difference in knee rotation
**Hip Flexion**
- Both groups land with small knee flexion
- ACL injured demonstrate greater peak flexion

**Hip Adduction**
- ACL injured land in more adducted position

**Hip Rotation**
- ACL injured land in more externally rotated position
“Prospective Profile” of ACL Injured

↓ Knee Flexion

↓ Hip Flexion

↓ Flexion at Initial Contact

Knee Valgus (Initial Contact)

↑ Hip ADDuction

Valgus Alignment at Initial Contact

↑ Hip Flexion (Displacement)

↑ Hip External Rotation

Altered Hip Neuromuscular Control
NOTE

• This is NOT a study of injury mechanisms
  – No-one tore their ACL during testing
• This is a study that helps us:
  – Identify and screen-out individuals with high-risk movement patterns
  – Many years prior to injury
Some findings agree with non-contact ACL injury mechanisms -- some do not

- ↓ Knee Flexion
- ↓ Hip Flexion
- ↑ Knee Valgus (Initial Contact)
- ↑ Hip ADDuction
- ↑ Hip Flexion (Displacement)
- ↑ Hip External Rotation

Ireland, 1998
Multiple Factors Affect ACL Loading

ACL Loading

ACL

Task Factors

Jump-Landing
Cutting
Stopping
Multiple Factors Affect ACL Loading

Low Risk Movement Pattern

High Risk Movement Pattern

Movement Factors
Multiple Factors Affect ACL Loading

High Risk Movement Pattern

Low Risk Movement Pattern

Jump-Landing
Cutting
Stopping

ACL Loading

ACL
Multiple Factors Affect ACL Loading

Low Risk Movement Pattern

High Risk Movement Pattern

ACL Loading

ACL

Jump-Landing

Cutting

Stopping
Multiple Factors Affect ACL Loading

ACL Loading

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Jump-Landing

Cutting

Stopping

ACL Loading

ACL
Multiple Factors Affect ACL Loading

Low Risk Movement Pattern

High Risk Movement Pattern

ACL Loading

Jump-Landing
Cutting
Stopping
Multiple Factors Affect ACL Loading

- Distracted
- Misjudgement
- Defender Moves
- Foot Slips
- Pushed

Unanticipated + Low Risk Movement
Multiple Factors Affect ACL Loading

- Misjudgement
- Foot Slips
- Pushed

Unanticipated + Low Risk Movement

ACL Loading

Defender Moves
Distracted

Jump-Landing
Cutting
Stopping
Multiple Factors Affect ACL Loading

- Misjudgement
- Foot Slips
- Pushed

Unanticipated + Low Risk Movement

ACL Loading

- Defender Moves
- Distracted

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Stopping
Multiple Factors Affect ACL Loading

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Unanticipated + High Risk Movement

ACL Loading

ACL

Defender Moves
Distracted

High Risk Movement Pattern

Jump-Landing
Cutting
Stopping
Multiple Factors Affect ACL Loading

- Misjudgement
- Foot Slips
- Pushed

Unanticipated + High Risk Movement

ACL Loading

ACL Injury

High Risk Movement Pattern

Defender Moves

Distracted
• How can this information provide insight into rehabilitation and return to participation decisions in ACL injured?
Previous History of ACL Surgery
Non-Contact / Indirect Contact ACL Injury (excluded Direct Contact)

N=150 Prior ACL Inj.
13 re-injuries (8.7%)

N=5,758 No ACL Inj.
78 primary injuries (1.4%)

Rate Ratio = 6.9; 95%CI: 3.8, 12.4; p<0.01
Q: Bad Workmanship or Biomechanics?  
A: Bad Biomechanics

<table>
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<tr>
<th>Prior ACL Injury Side</th>
<th>Left</th>
<th>Right</th>
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<td>Left</td>
<td>3</td>
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<td>Right</td>
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<td>Both</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Total</td>
<td>6</td>
<td>6</td>
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</table>

Equal risk for ipsilateral and contralateral sides
Knee Flexion Angle

Time (Percent Stance Phase)

↑ Knee flexion motion

- No Injury History
- Primary ACL Injury
- Prior ACL Injury
Knee valgus at IC

- No Injury History
- Primary ACL Injury
- Prior ACL Injury
Hip Flexion Angle (Flx-Ext+)

-80
-70
-60
-50
-40
-30
-20
-10
0

Time (Percent Stance Phase)

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

**No Injury History**

**Primary ACL Injury**

**Prior ACL Injury**

↑ Hip Flexion Motion

↑ Hip Flexion at IC
Hip Rotation Angle (Ext-Int+)

-12
-11
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2

Time (Percent Stance Phase)

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

-12
-11
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2

Hip ER at IC

No Injury History

Primary ACL Injury

Prior ACL Injury
Hip Adduction Angle (Abd-Add+)

Time (Percent Stance Phase)

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

No Injury History
Primary ACL Injury
Prior ACL Injury

↑ Hip ADDuction at IC
Movement Patterns

- Healthy ≠ ACL injured (primary & prior)
- Primary ACL Injury = Prior ACL Injury
Causation or Compensation?

Prior to Initial Injury (causation)

↓ Knee Flexion

↓ Hip Flexion

↑ Knee Valgus (Initial Contact)

↑ Hip ADDuction

↑ Hip Flexion (Displacement)

↑ Hip External Rotation

After Initial Injury (compensation)

↑ Hip Flexion (Initial Contact)

↓ Int. Knee Extension Moment

↑ Knee Flexion (Displacement)
Compensatory Movement Pattern Development

- **↓ Quadriceps Function**
  - **↓** Strength (*Palmieri-Smith et al, 2008; Ingersoll et al, 2008*)
  - **↓** Activation (*Hart et al, 2008; Ingersoll et al, 2008*)
  - **↓** Extension moment (*Hart et al, 2010; Ingersoll et al, 2008*)

After Initial Injury (compensation)

↑ Hip Flexion (Initial Contact)

↓ Int. Knee Extension Moment

↑ Hip Flexion (Displacement)
Normal Quadriceps Function

Quadriceps Dysfunction Compensation

↑ Knee Flexion (Displacement)

↓ Int. Knee Extension Moment

↑ Hip Flexion (Initial Contact)
Quadriceps Dysfunction

- Exacerbate faulty movement patterns associated with initial injury risk
  - ↑ Hip Flexion (Anterior Pelvic Tilt)
  - ↑ Hip ADDuction
  - ↑ Hip Flexion (Displacement)
  - ↑ Hip External Rotation
  - ↑ Knee Valgus (Initial Contact)
  - ↑ Int. Knee Varus Moment (Ext. Valgus)
↑ Pelvo-Femoral Flexion (Anterior Pelvic Tilt)

↓ Superior Migration of Posterior Pelvis

↑ Length of GMAX & Hamstrings

↓ Force Production

↑ Reliance on synergistic hip extensor muscles to decelerate hip flexion

Alters mechanical function of hip musculature
Hip Extension

GMED post.

GMAX

Hamstrings

ADD Magnus

Hip Flexion

GMIN ant.

TFL
Sartorius
Rectus Femoris

IP

ADD Brevis
ADD Longus
Gracilllis
Pectineus

Neumann, JOSPT 2010
↑ Pelvo-Femoral Flexion

Reversal of Lever Arm (direction of pull)

• Hip ADDuctors (except adductor magnus, already hip extensor)
  – ↑ Hip Flexion → Extension lever arm

Neumann, JOSPT 2010
Hip Extension

- GMAX
- Hamstrings
- ADD Magnus

Hip Flexion

- GMED post.
- GMIN ant.
- TFL
- Sartorius
- Rectus Femoris
- ADD Brevis
- ADD Longus
- Gracilis
- Pectineus

Neumann, JOSPT 2010
Hip Extension

- GMED post.
- GMAX
- Hamstrings
- ADD Magnus

Hip Flexion

- GMIN ant.
- TFL
- Sartorius
- Rectus Femoris
- ADD Brevis
- ADD Longus
- Gracillis
- Pectineus

Synergistic Dominance

↓

↑ Hip ADDuction Moment

Neumann, JOSPT 2010
↑ Pelvo-Femoral Flexion

Reversal of Lever Arm (direction of pull)

- Hip External Rotators (piriformis, gluteus medius – post, gluteus maximus – ant)
  - ↑ Hip Flexion → Internal Rotation lever arm

Increase of Lever Arm (M = F * d)

- Dramatically increases the lever arm of hip internal rotators
  - ↑ Hip Flexion → ↑ Internal Rotation lever arm
Hip Internal Rotation

ADD Longus
ADD Brevis
Obturator ext.

Pectineus

GMIN ant.
GMED ant.

GMED post.

GMIN post.
Quadratus Femoris
Gemellus sup.
Obturator int.
Gemellus inf.
Piriformis
GMAX

Hip External Rotation

Neumann, JOSPT 2010
Hip Internal Rotation

ADD Longus
ADD Brevis
Obturator ext.

Pectineus
GMIN ant.
GMED ant.

GMED post.

GMIN post.
Quadratus Femoris
Gemellus sup.
Obturator int.
Gemellus inf.
Piriformis
GMAX

↑ Hip Internal Rotation Moment

Hip External Rotation
Quadriceps Dysfunction Post ACL Injury

↑ Hip Flexion (IC) (Ant. Pelvic Tilt)

↑ Length of GMAX & HAMS

Alters Length-Tension → ↓ Force

Synergistic Dominance

↑ Hip Flexion (Displacement)

↑ Knee Valgus (Initial Contact)

↑ Knee Valgus Moment

↑ Hip ADDuction

↑ Hip External Rotation

↓ Int. Knee Extension Moment

↑ Knee Flexion Displacement

Compensatory Movement Patterns

Exacerbate Faulty Movement Patterns
Implications

Prevention

• Prevention of ACL injury / re-injury may be possible by modifying high risk movements

Rehabilitation

• Movement quality should be part of exercise progression & return to participation criteria
  – Returning to pre-injury status is NOT sufficient
Achieve **Excellent** Movement Quality

- **Symmetrical** movement quality is **not** sufficient
  - Uninjured side should **not** be used for comparison
  - Faulty movement patterns were likely already present (reason for ACL injury)

- **Consistently assess** movement quality

- **Use systematic movement assessment** to guide exercise progression
  - Movement Assessment Progression of Exercise
    - “Exercise MAP”
Movement Assessment
Overhead Squat Test

Neutral Alignment
Movement Assessment
Overhead Squat Test

Neutral Alignment
Movement Impairments Associated with ACL Injury

Common Movement Impairments:
- Foot external rotation (toe out)
- Foot flat (pronation)
- Limited ankle dorsiflexion (heel lift)
- Knee valgus (knee moves inward)
- Excessive trunk / lumbopelvic flexion
- Asymmetric weight shift
Movement Impairments

Toe Out

Heel Lift
Movement Impairments

Foot Flat

Knee Valgus
Movement Impairments

Excessive Trunk Flexion or Lumbopelvic Flexion

Asymmetric Weight Shift
Landing Error Scoring System (LESS)

- Drop height = 30 cm
- Horizontal distance = 50% body height
- Jump for maximum vertical height after landing
- Focus on initial landing and max knee flexion
- Quantify the number of movement errors
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<th>Description</th>
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<td>1.</td>
<td>Knee Flexion @ Initial Contact: &gt; 30 degrees</td>
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<td>Yes 0</td>
<td>No +1</td>
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<td>Knee Valgus @ Initial Contact: Knees over midfoot</td>
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<td>Yes 0</td>
<td>No +1</td>
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<td>Hip Flexion @ Initial Contact: Hips are flexed</td>
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<td>Yes 0</td>
<td>No +1</td>
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<td>Trunk Flexion @ Initial Contact: Trunk is flexed</td>
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<td></td>
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<td>No +1</td>
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<td>Lateral Trunk Flexion @ Initial Contact: Trunk is vertical</td>
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<td>Sternum centered over hips 0</td>
<td>Lateral deviation of sternum over hips +1</td>
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<td>No +1</td>
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<td>Foot Position @ Initial Contact: Toes &gt; 30 of ER</td>
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<td></td>
<td>Yes +1</td>
<td>No 0</td>
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<td>Foot Position @ Initial Contact: Toes &gt; 30 of IR</td>
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<td></td>
<td>Yes +1</td>
<td>No 0</td>
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<td>Stance Width @ Initial Contact:&lt; Shoulder width</td>
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<td>Yes +1</td>
<td>No 0</td>
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<td>Stance Width @ Initial Contact: &gt; Shoulder width</td>
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<td>Initial Foot Contact: Symmetric</td>
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<td>Knee Flexion Displacement: &gt; 45 degrees</td>
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<td>No 1</td>
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<td>Trunk Flexion Displacement: Trunk flexes more than at initial contact</td>
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<td>Joint Displacement (Sagittal Plane)</td>
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<td>17.</td>
<td>Overall Impression</td>
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<td>Excellent 0</td>
<td>Average +1</td>
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</table>
Pre-season LESS scores are higher in those who go on to tear their ACL

- 761 youth soccer athletes
- 6 suffered ACL injury

Padua et al, J Ath Train, 2010
LESS prospectively identifies ACL injured

ROC Curve Analyses

LESS Cutoff Score = 5
Sensitivity = 83%
Specificity = 67%

Similar to external knee valgus moment
Sensitivity = 78%
Specificity = 67%

Hewett et al, 2005

Padua et al, J Ath Train, 2010
Muscle Imbalance → Movement Impairments

Muscle Balance

- Equivalent force / tension → Equilibrium

Muscle Imbalance

- Unequal force / tension → Mal-alignment

- Tight or Overactive
- Weak or Inhibited
Example Strategy for Knee Valgus Movement Impairment
Corrective Exercise Strategy (CES)

4 Step Process to Restore Muscle Balance:
1. Inhibit overactive muscles
2. Lengthen overactive & shortened muscles
3. Activate inhibited & weak muscles
4. Integrate all muscles & neuromuscular system into functional movement patterns
1) Inhibit Overactive / Tight Muscles

Application Guidelines:
• Apply to overactive / tight muscles
• 30 second hold per tender area
• ↓ discomfort noted
2) **Lengthen Overactive / Tight Muscles**

**Application Guidelines:**

- Apply to overactive / tight muscles
- 30 second hold
- 1-2 sets per muscle
3) **Activate Weak / Inhibited Muscles**

- **Gluteus Medius**
- **Gluteus Maximus**

**Side Lying Leg Lift**

**Hip Bridge**

**Application Guidelines:**
- Apply to weak / inhibited muscles
- 10-15 repetitions
- 2 sec isometric
- 4 sec eccentric
4) **Integrate for Neuromuscular Control**

Application Guidelines:
- Stress the muscle imbalances
- 10-15 repetitions (controlled)
- Proper technique is critical

Single Leg Balance Reach (multi-planar)
Sagittal

Frontal

Transverse

Multiplanar Hops to Balance
Squat Jump with Stabilization

Box Jump Up with Stabilization
Squat Jump

Tuck Jump
Ice Skater

Proprioceptive Plyometrics
Things to Emphasize

Land “Softly”
Bend Knees & Hips

Keep Knees Over Toes & Toes Straight Ahead
Systematic Progression: Exercise MAP

**Phase 1** (0-6 Weeks)
- Symmetric AROM
- Quad Control (SLR 3x20)
- Single Leg Balance (firm surface)
- Double Leg Squat

**Phase 2** (6-14 Weeks)
- Symmetric AROM
- Single Leg Squat (30°)
- Single Leg Balance (foam surface)
- 80% Strength of Uninjured Side

**Phase 3** (14-20 Weeks)
- Double Leg Jump-Landing (sagittal)
- Single Leg Squat (60°)
- Hop to Stabilization (tri-planar)
- 100% Strength of Uninjured Side

**Phase 4** (14-20 Weeks)
- Double Leg Jump-Landing (tri-planar)
- Lunges (triplanar)
- Single Leg Landing (sagittal)
- Symmetrical Running
Systematic Progression: Exercise MAP

Phase 5 (20-24 Weeks)
- Single Leg Landing (triplanar)
- Repeated Squat Jumps

Phase 6 (20-24 Weeks)
- Double Leg Jump Landing to Sprint (triplanar)
- Ice Skaters

Phase 7 (20-24 Weeks)
- Double Leg Jump Landing to Anticipated Cut (triplanar)
- Single Leg Landing to Sprint (triplanar)

Phase 8 (20-24 Weeks)
- Double Leg Jump Landing to Unanticipated Cut (triplanar)
- Single Leg Landing to Anticipated Cut (triplanar)
Return to Play Considerations

• Able to perform Phase 7 & 8 tasks:
  – Under fatigued conditions without movement compensations
  – Under dual task conditions without movement compensations
    • Catching
    • Throwing
Quality Movement Matters

• ↑ Faulty movement patterns ➔ ➥ Functional outcomes & performance (*Trulsson et al, 2010*)

  – Battery of 9 movement tasks:

    1) Single leg bridge
    2) Weight shift
    3) Single leg squat
    4) Single leg heel raise
    5) Single leg balance on unstable surface
    6) Stand from half-kneeling
    7) Forward lunge
    8) Backward walking (t-mill)
    9) Double leg squat
Quality Movement Matters

• **Risk of second ACL injury** *(Paterno et al, 2010)*
  - Hip IR moment (uninvolved leg) *(8x)*
  - **Frontal plane knee motion** (involved leg) *(3.5x)*
  - Asymmetrical knee extension moment *(3x)*
  - **↓ Single leg postural stability** (involved leg) *(2x)*

• 3D biomechanical analyses is best determinant of readiness for return to play
  - Sensitivity = 92%
  - Specificity = 88%
Problem Solved?

• Barriers exist for widespread injury prevention efforts
  – Compliance
  – Supervision
  – Retention
  – Pediatric population
Compliance Rates Influence Effectiveness

• Myklebust et al, 2003
  – Unchanged ACL injury rate (28% compliant)
  – Sub-group analysis of highly compliant players (elite division) demonstrated ↓ ACL injury risk

• Steffen et al, 2008
  – Unchanged ACL and lower extremity injury rates (44% compliant)

• Soligard et al, 2009
  – Divided intervention subjects into tertiles
  – 35% lower injury risk in most compliant group
# Improving Biomechanics Requires Supervision & Instruction

<table>
<thead>
<tr>
<th>Study</th>
<th>Direct Supervision</th>
<th>Technique Instruction</th>
<th>Outcome</th>
<th>% Change</th>
<th>Effect Size</th>
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<td>Hewett, 1996</td>
<td>Yes</td>
<td>Yes</td>
<td>↓ VGRF</td>
<td>-18.0%</td>
<td>0.87</td>
</tr>
<tr>
<td>Prappavessis, 2003</td>
<td>Yes</td>
<td>Yes</td>
<td>↓ VGRF</td>
<td>-33.3%</td>
<td>0.79</td>
</tr>
<tr>
<td>Irmischer, 2004</td>
<td>Yes</td>
<td>Yes</td>
<td>↓ VGRF</td>
<td>-26.4%</td>
<td>1.4</td>
</tr>
<tr>
<td>Herman, 2008</td>
<td>Yes</td>
<td>No</td>
<td>No change</td>
<td>-3.1%</td>
<td>0.07</td>
</tr>
<tr>
<td>Chappell, 2008</td>
<td>No</td>
<td>No</td>
<td>No change</td>
<td>1.6%</td>
<td>0.07</td>
</tr>
<tr>
<td>Lephart, 2005</td>
<td>No</td>
<td>No</td>
<td>No change</td>
<td>-4.2%</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Important Considerations

Changes in movement quality are **NOT** retained when achieved over a short training period (3 months)

Padua et al, AJSM, 2011
Children Require Different Training

- Biomechanics not improved in pediatric populations


Grandstand et al., *J Str Cond Res*, 2006

- No improvement in:
  - Medial knee displacement
  - Vertical jump height
Key Points

- Previous ACL injury history = Risk factor

- Similar risk factors for ACL injury and re-injury
  - Faulty movement patterns

- Important factors for success
  - Restore quadriceps function
  - Achieve “excellent” movement quality
  - Return to pre-injury/uninjured side status is not sufficient
    - Faulty movement patterns pre-disposed to initial injury
Acknowledgements

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