Rupture mechanisms in anterior cruciate ligament injury: The quest for prevention methods

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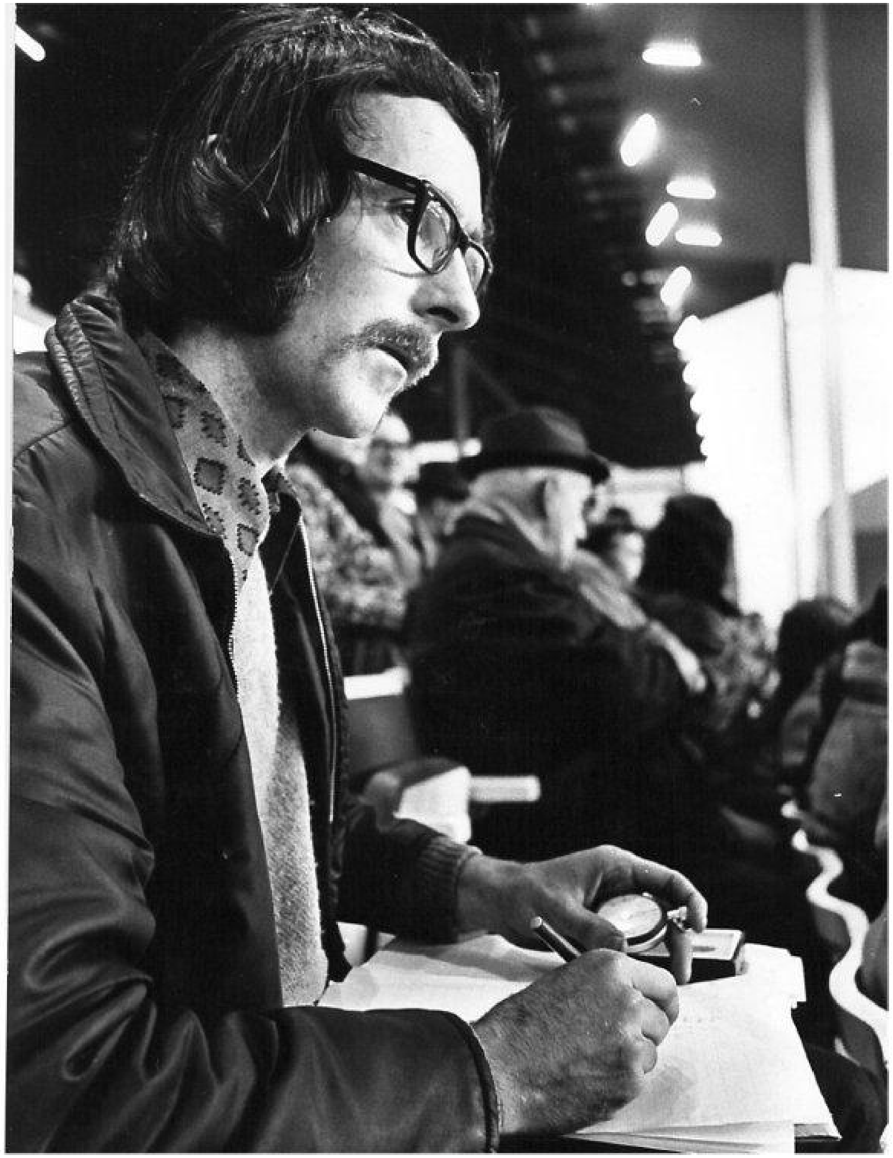

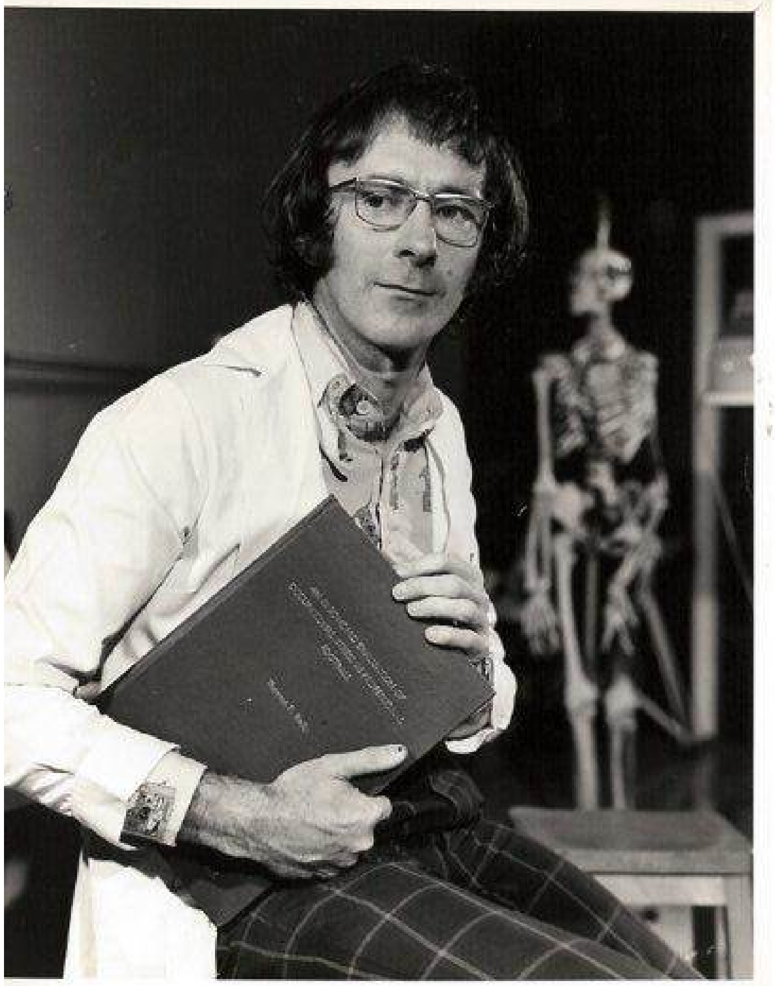

dream plan achieve

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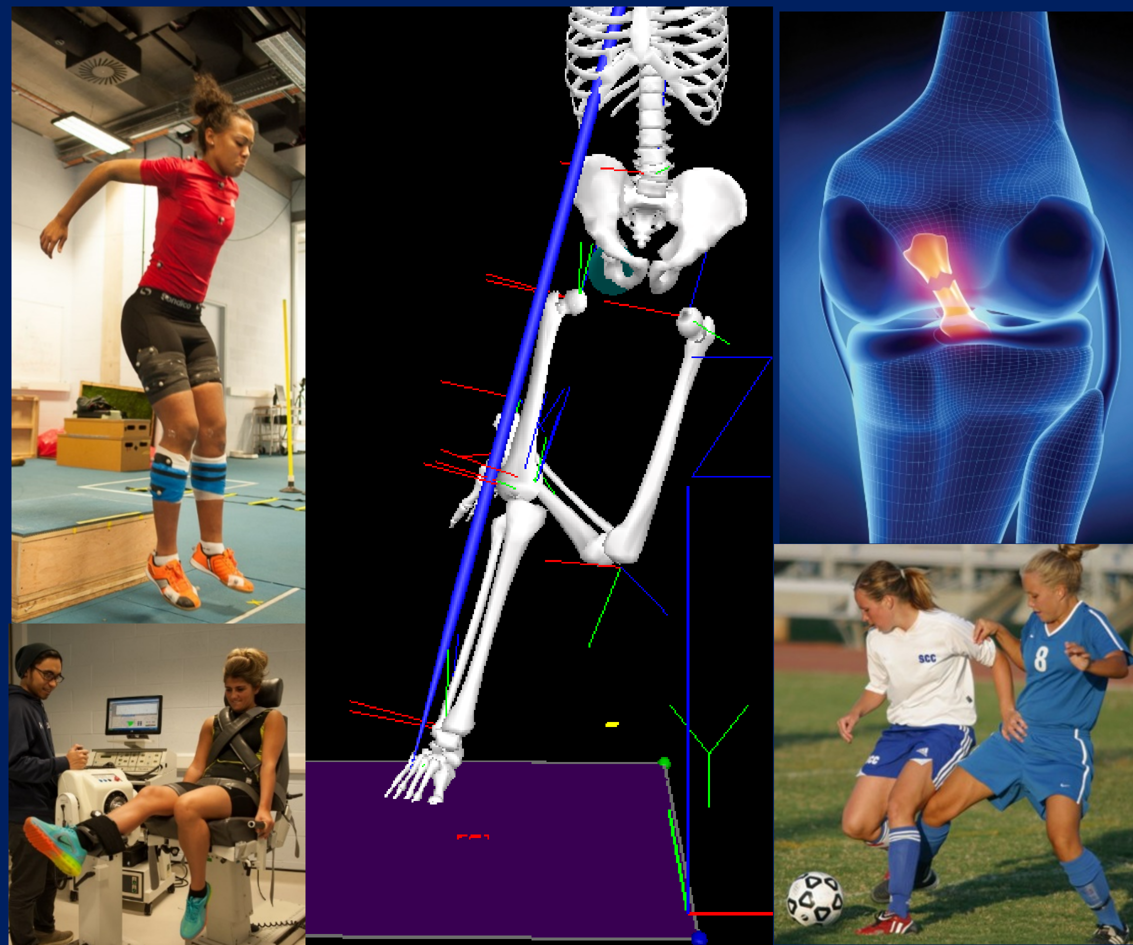
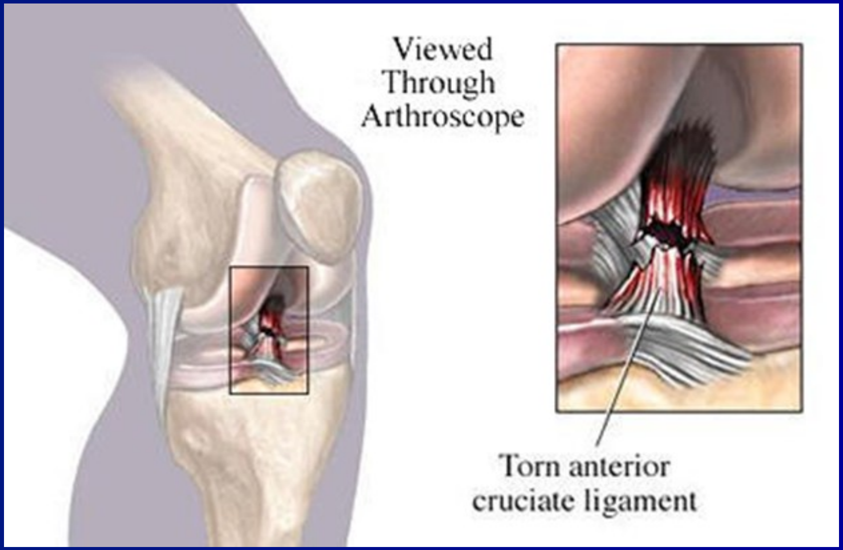
The Liverpool Knee Study

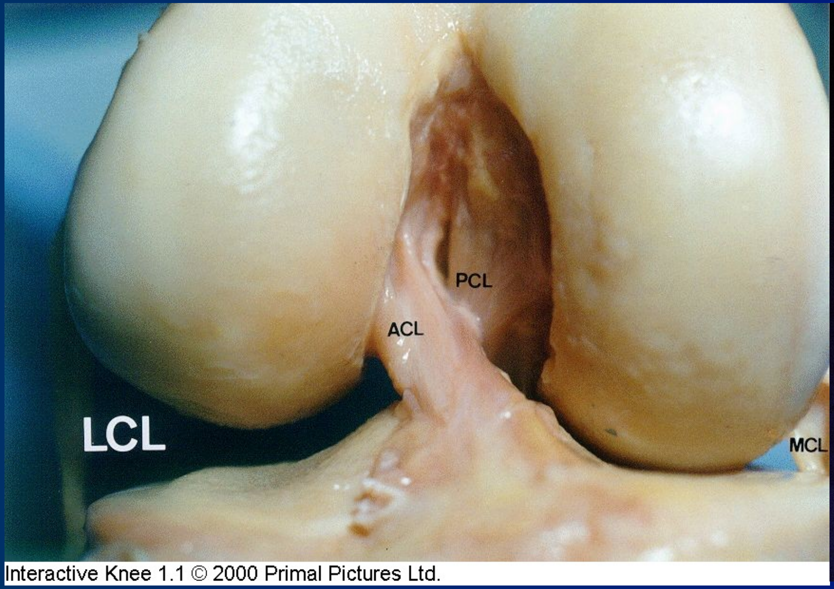


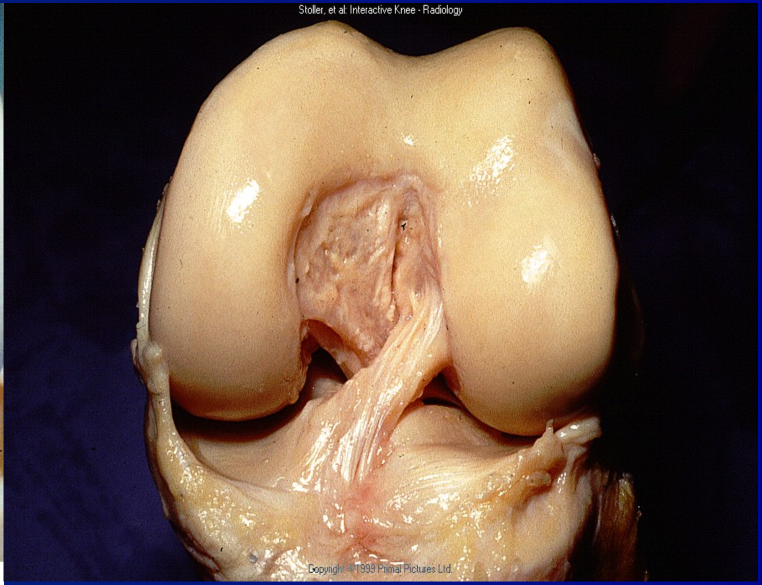
The Problem of ACL Injuries

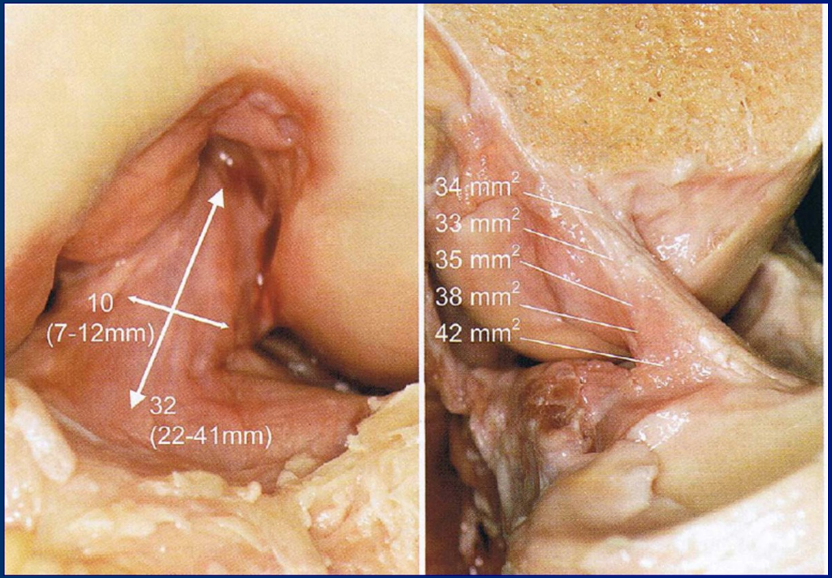
- 30 new cases per 100.000 population per year
- 100,000 injuries/year in U.S.
- ½ of all ligamentous knee injuries
- 1/3000 people will suffer ACL injury in any given year
- 70% will occur during sporting activity
- 6:1 female to male ratio

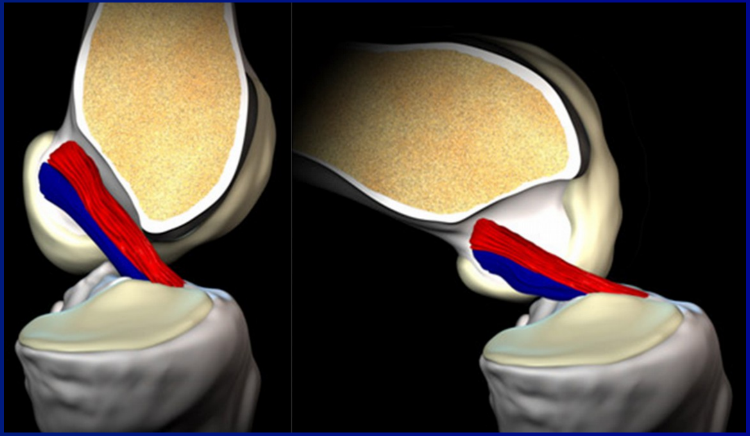


Anterior Cruciate Ligament (ACL)



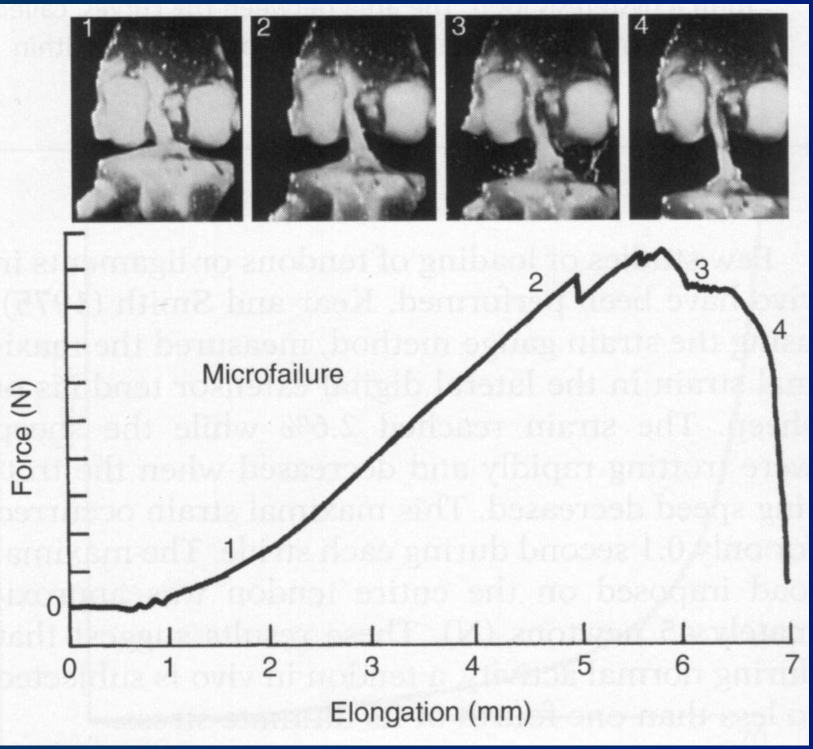






http://www.radsource.us/rf/RADS/Default.aspx

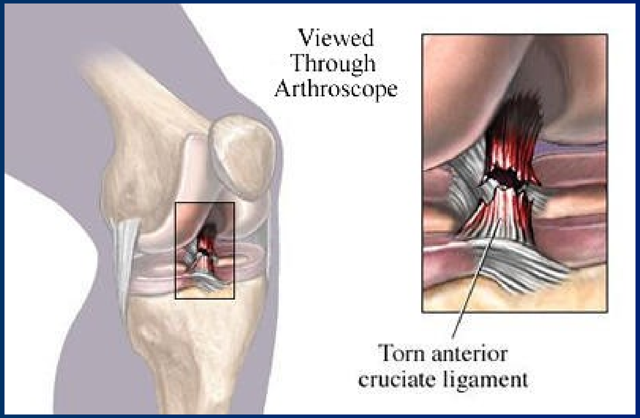
ACL - Biomechanics



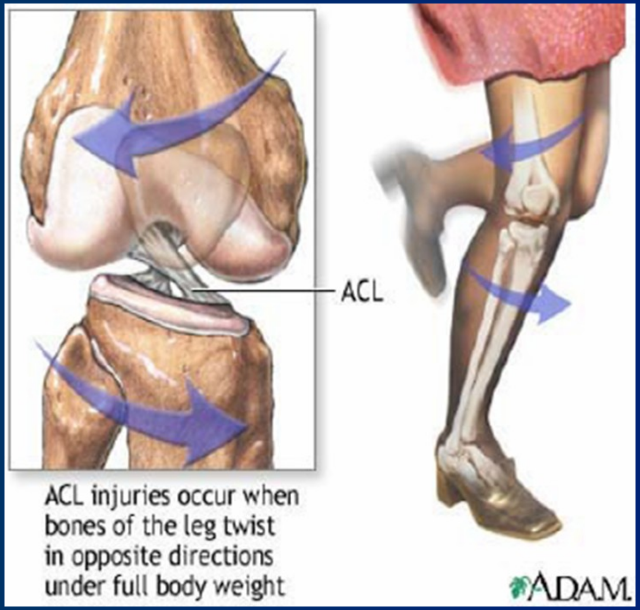
- Maximum load of the young anterior cruciate ligament (22-35 years) is ~2200 N
- This decreases to approximately one third of this value for older knees
- The strain at yield is reported in the region of 10-30% depending on strain rate and age
- Stiffness of 80-240 N/mm for the whole anterior cruciate ligament have been reported in the literature. The higher values are for young and mature knees, the lower values are for knees over 60 years old
- Young's Modulus ~300 MPa and the Maximum Stress is reported between 15 and 45 MPa

Butler et al., 1985; Woo et al., 1991

ACL Injury Mechanism

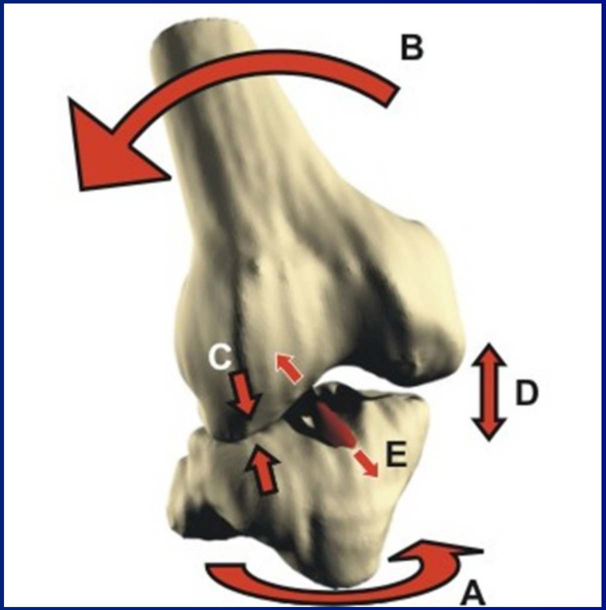


Movements of the knee that place a great **strain** on the ACL can cause damage to the ligament.

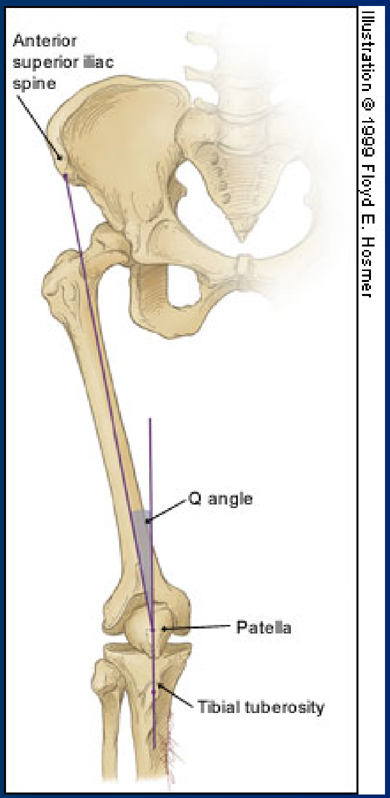


Rotational Movement Loading through combination of Tibial Rotation with the Knee in Extension or Flexion

Mechanism of combined loads in ACL rupture



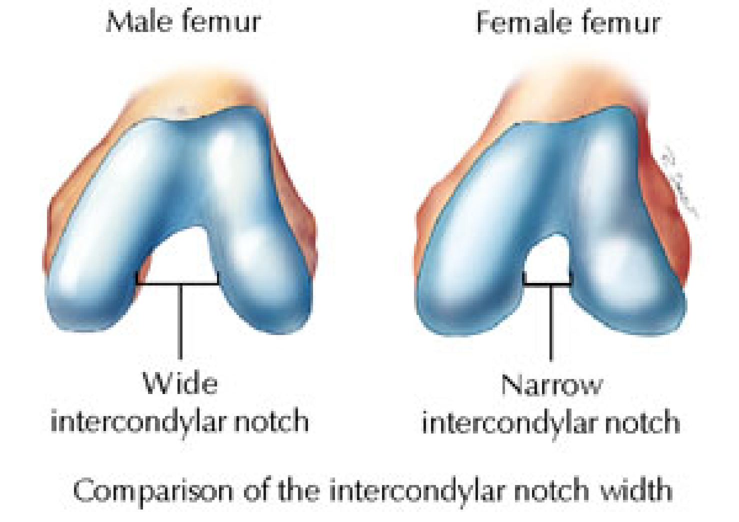
Female Athletes-Risk Factors



Anatomical Factors:

- Lower extremity alignment
- Higher Q Angle
- Knee Valgus

Female Athletes-Risk Factors



Anatomical Factors:

- Narrower intercondylar notch
- ACL function affected
- Intercondylar notch is smaller in athletes with ACL injuries

e.g. Harner et al. (1994) AJSM

ACL Injury – Risk Factors
Gender

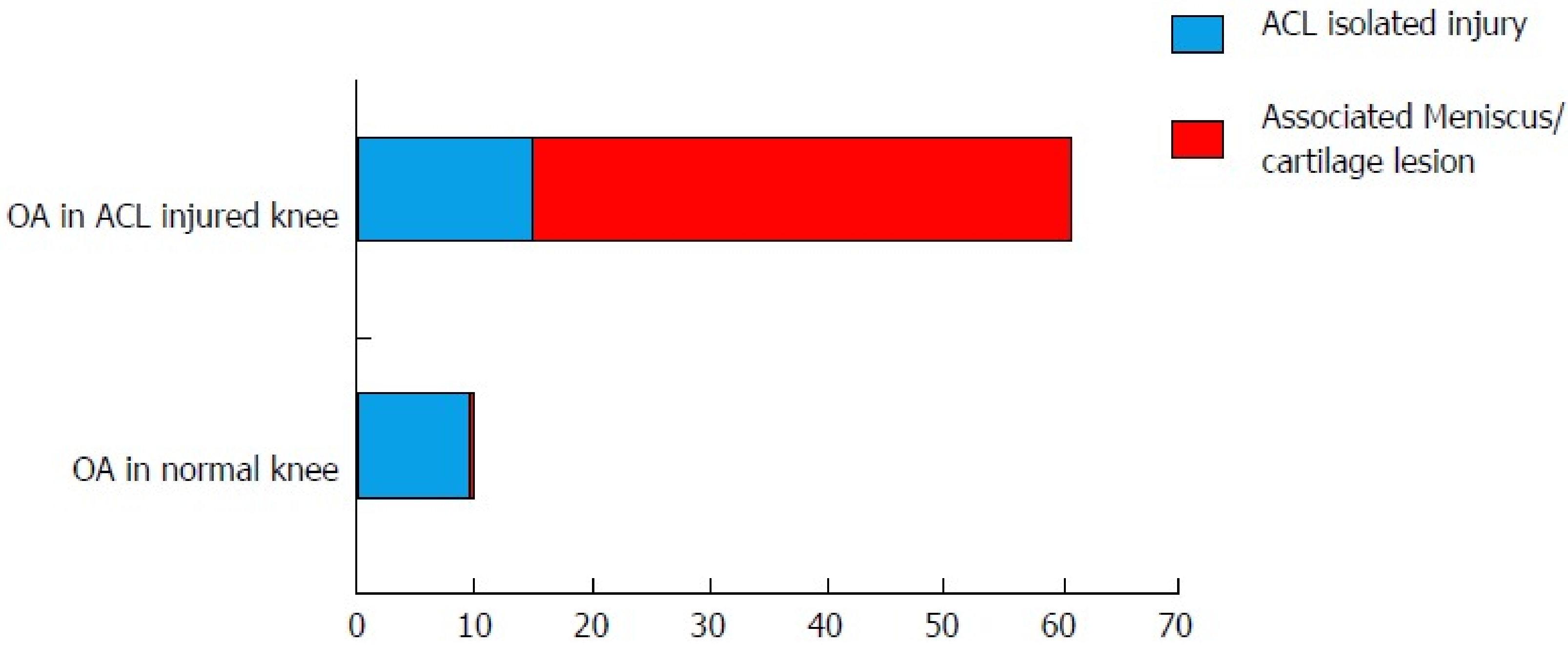
Females:

- 6-8 higher injury rate
- Land with knees less flexed
- Poor hamstrings:quadriceps balance
- Hamstrings protection of ACL reduced
- Hamstring co-activation deficit
- Slow activation of hamstrings

The 'position of no return' for ACL injury:

- Hip usually Forward Flexed & Abducted
- Knee internally/externally rotated with valgus
- Foot pronated

The consequences of ACL Injury



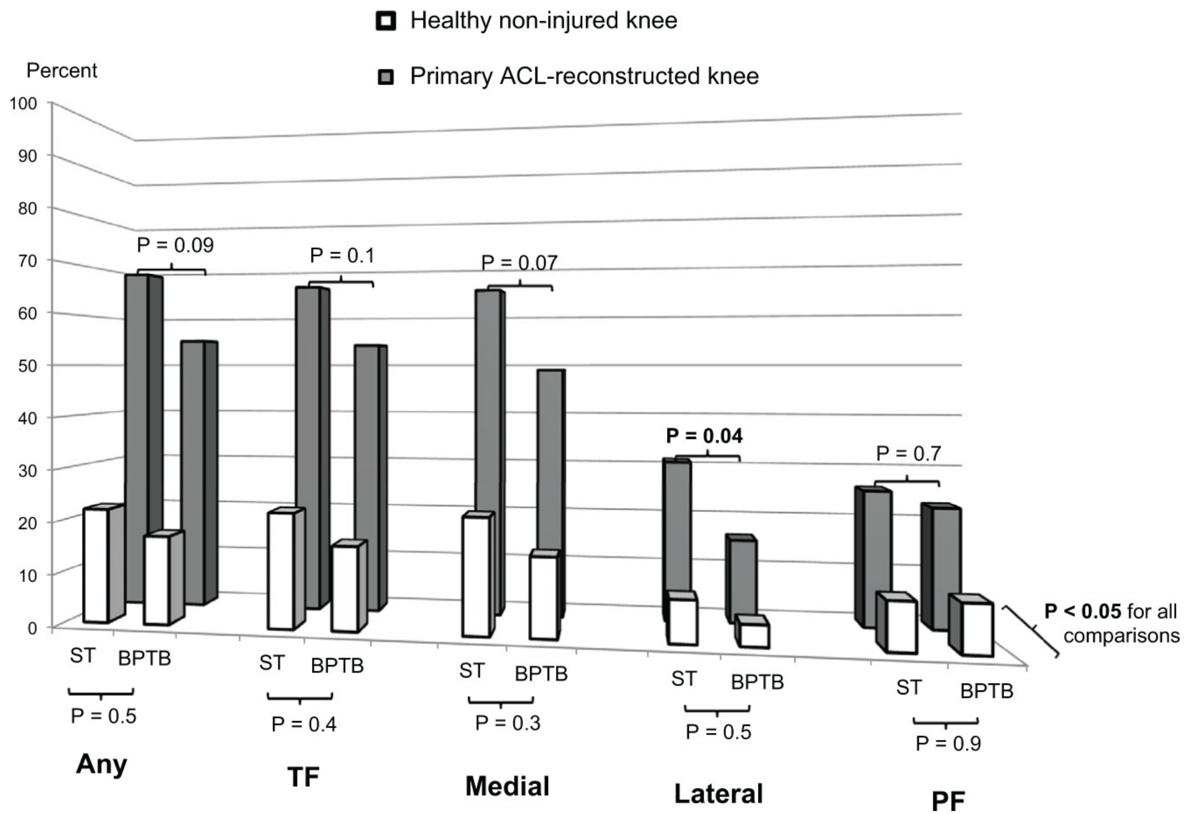
Paschos, N. K. (2017). Anterior cruciate ligament reconstruction and knee osteoarthritis. World Journal of Orthopedics, 8(3), 212–217. http://doi.org/10.5312/wjo.v8.i3.212

The consequences of ACL Injury

- Research demonstrates that adolescents and young adults who sustain an ACL injury are at a substantially increased risk for the development of future osteoarthritis (OA) in the patellofemoral and tibiofemoral joints
- OA in this situation is defined by objective structural findings including cartilaginous wear or joint-line changes via radiographic imaging or direct visualization.
- Some studies suggest that as many as 80% of ACL injured knees may demonstrate radiographic evidence of OA at 5 to 15 years after initial injury, especially with concomitant meniscal damage

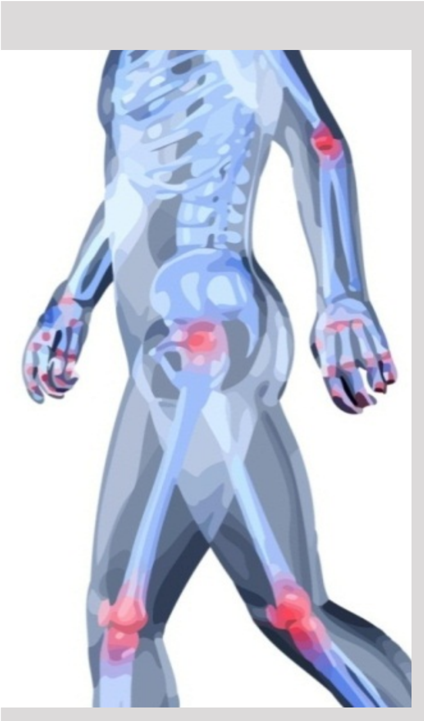
Simon D., Mascarenhas R., Saltzman B., Rollins M., Bach B. Jr., and MacDonald P.
The Relationship between Anterior Cruciate Ligament Injury and Osteoarthritis of the Knee, Advances in Orthopedics, Volume 2015 (2015), http://dx.doi.org/10.1155/2015/928301

The consequences of ACL Injury



A 3-fold increased prevalence of OA was found after an ACL injury treated with reconstruction compared with the contralateral healthy knee.

Björn Barenius; Sari Ponzer; Adel Shalabi; Robert Bujak; Louise Norlén; Karl Eriksson; *Am J Sports Med* 42, 1049-1057.
DOI: 10.1177/0363546514526139,

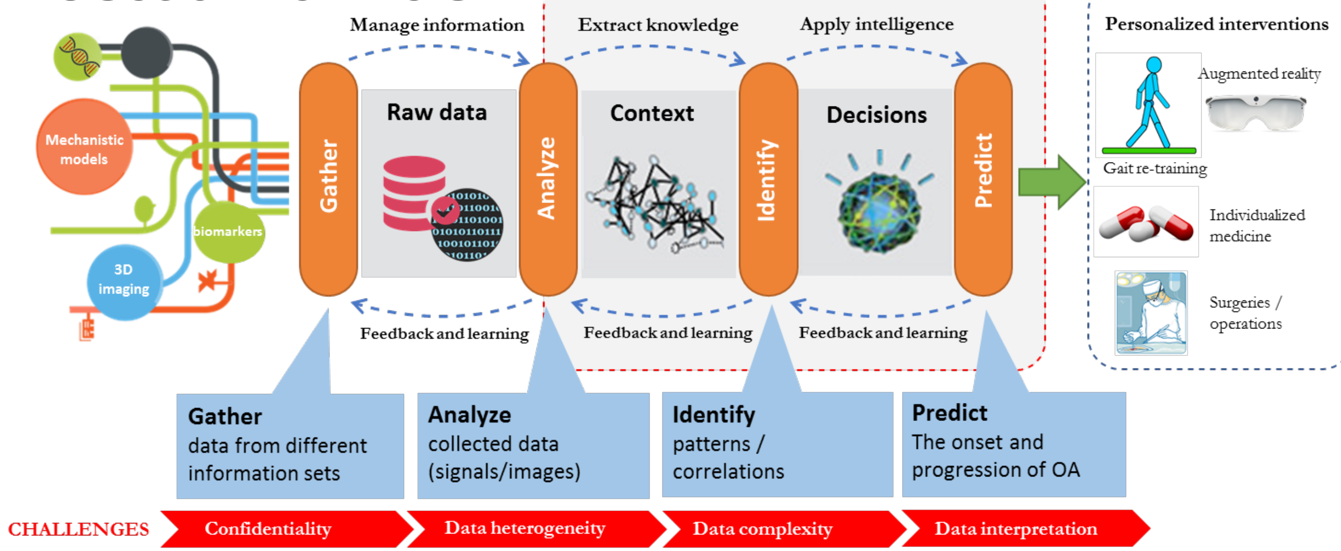


SC1-PM-17-2017 - Personalised computer models and in-silico systems for well-being

Grant agreement 777159
13 Partners
€ 4.9 M

OActive

Advanced personalised, multi-scale computer models preventing OsteoArthritis



Why is the problem of ACL prevention not solved?

Although we have made substantial strides forward, the sequence of prevention must be continued until there is substantial epidemiologic evidence that ACL injury risk is definitively decreased in young athletes.

Continued studies should include the assessment of relative injury risk using widespread neuromuscular screening techniques. Additional work toward the development **of more specific injury prevention protocols targeted to high-risk athletes** with determination of the timing of when these interventions should most effectively be used is imperative.

Clin Orthop Relat Res (2012) 470:2930–2940
DOI 10.1007/s11999-012-2440-2

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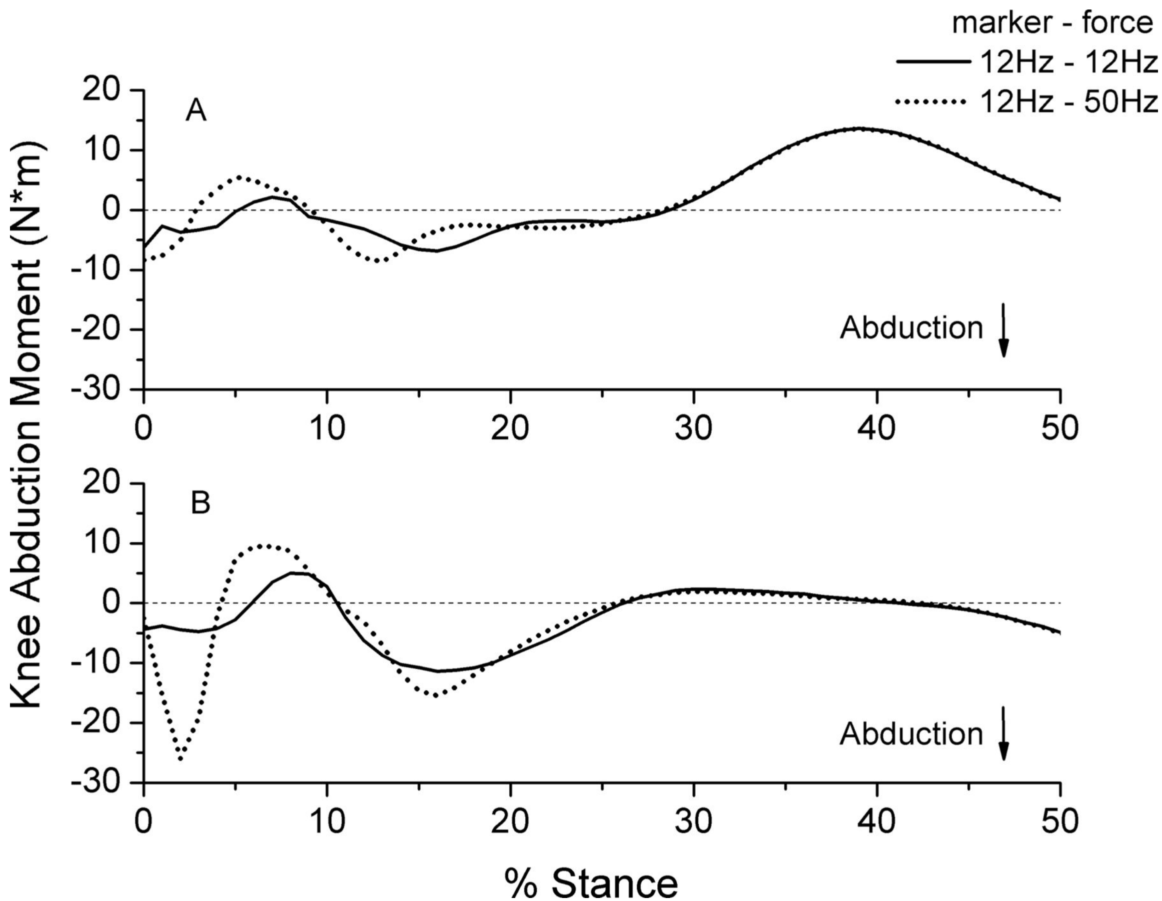
The Sequence of Prevention: A Systematic Approach to Prevent Anterior Cruciate Ligament Injury

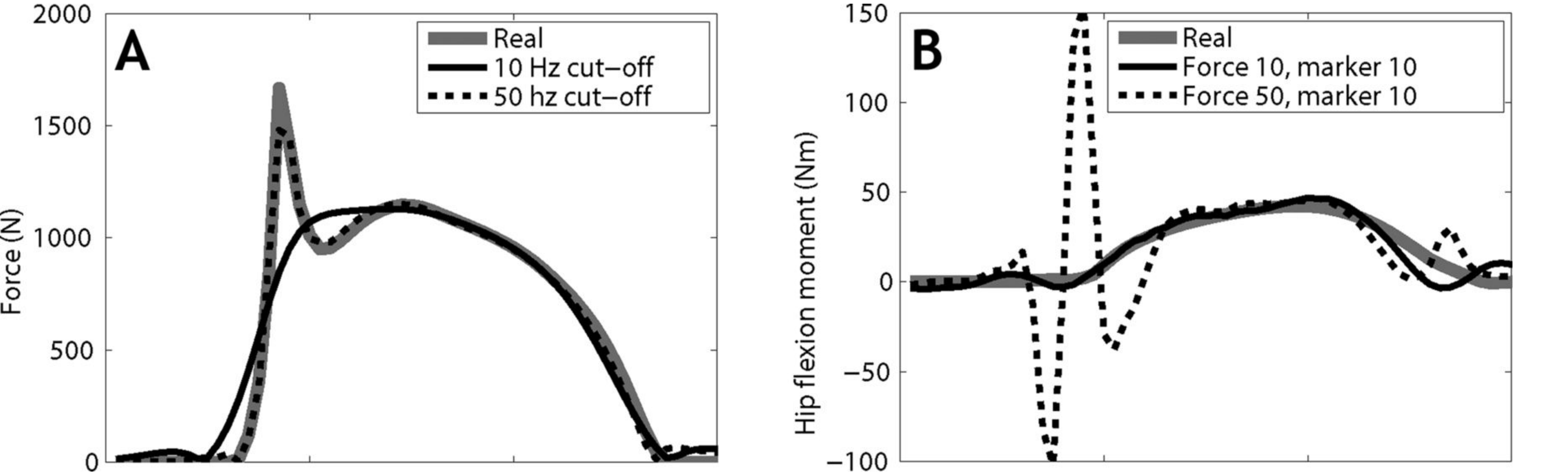
Timothy E. Hewett PhD, Gregory D. Myer PhD,
Kevin R. Ford PhD, Mark V. Paterno PhD, PT,
Carmen E. Quatman MD, PhD

Knee abduction moment (KAM) is currently the strongest reported single predictor of primary ACL injury in young female athletes, with a sensitivity of 78% and a specificity of 73%. However, using this biomechanical predictor to identify young athletes at risk of ACL injuries requires the ability to accurately measure joint moments using inverse dynamic techniques.



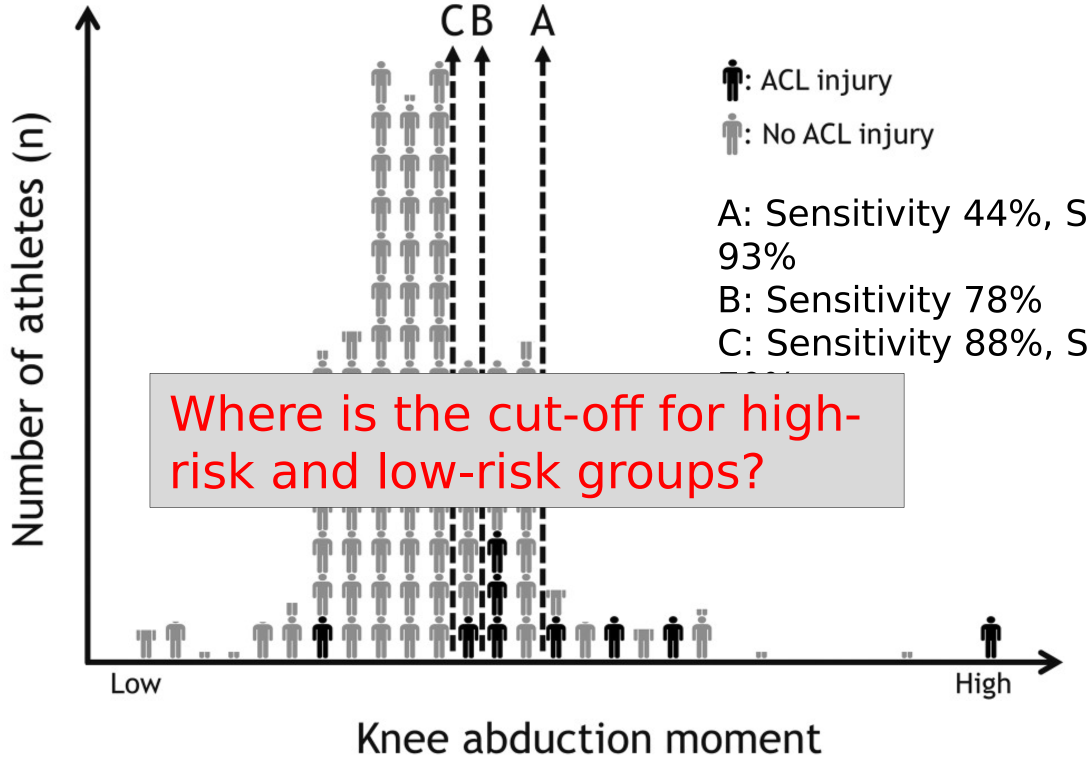
The averaged external knee abduction moment for two subjects produced using the same low cut-off frequency (solid line) and different cut-off frequencies (dashed line).

Roewer B D et al. Br J Sports Med 2014;48:464-468



Eirik Kristianslund, Tron Krosshaug, Antonie J van den Bogert, Artefacts in measuring joint moments may lead to incorrect clinical conclusions: the nexus between science (biomechanics) and sports injury prevention!
Br J Sports Med 2013;47:470-473, Editorial

Challenges of screening for ACL injury risk?
Are the risk factors sensitive enough?



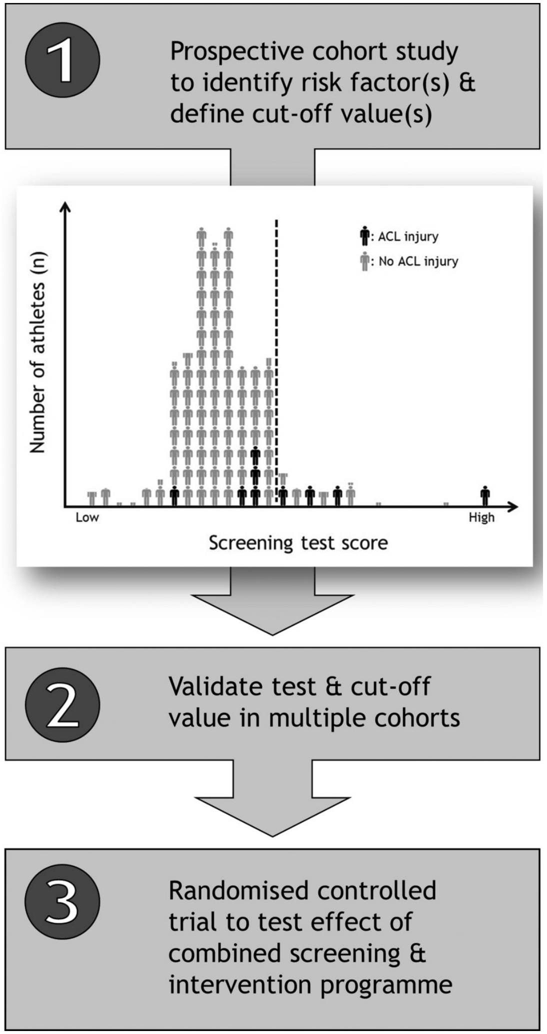
A: Sensitivity 44%, Specificity 93%
B: Sensitivity 78%
C: Sensitivity 88%, Specificity

Where is the cut-off for high-risk and low-risk groups?

Sensitivity and specificity are inversely related.
To capture all injured players (100% sensitivity), specificity suffers (more uninjured athletes will be classified as having high risk).
The positive predictive value is low in all scenarios, ranging from 14% to 7%.

Bahr, 2016, BJSM

Three research steps needed to develop and validate a screening programme.

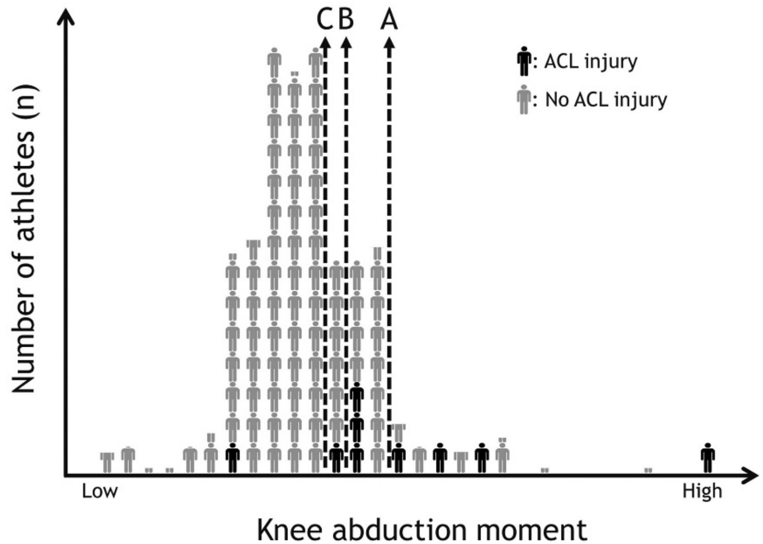


Roald Bahr, Why screening tests to predict injury do not work and probably never will…: a critical review Br J Sports Med 2016;50:776-780

Bahr vs Hewett

"Unfortunately, to date, there is ***no screening test available to predict sports injuries*** *with adequate test properties and no intervention study providing evidence in support of screening for injury risk".*

Roald Bahr, Br J Sports Med 2016;50:776-780



"Although it may be accurate that injury screening may not be able to 'predict' which individual is going to go on to subsequent injury, it can clearly be used ***to identify risk subgroups".***

Tim Hewett, Br J Sports Med 2016;50:1353.

BJSM

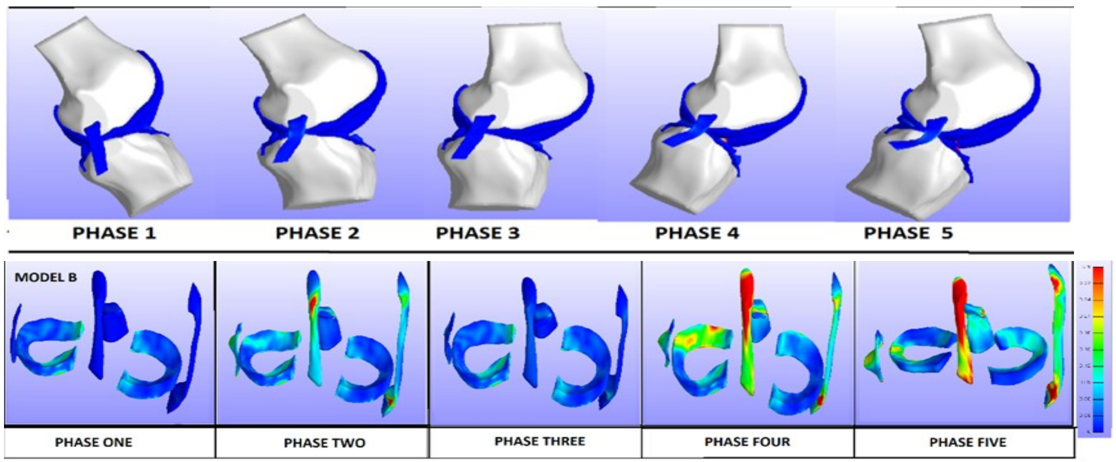
Why is the problem of ACL prevention not solved?

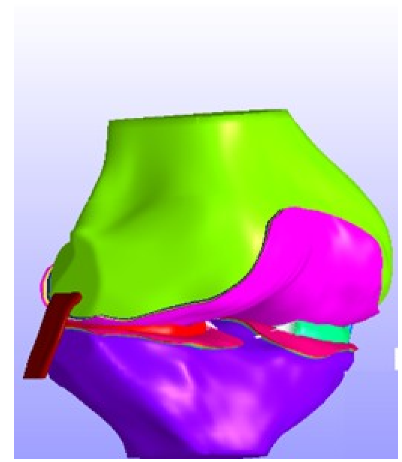
1. Risk Factors are based on various general ‘loading’ variables but not direct ACL strain

2. The loading throughout the movement sequence is not taken into consideration

3. The biomechanics of the knee joint and ACL mechanics change in-vivo during movement

Combination of Finite Element Modelling (FEM) and Musculoskeletal Model (opensim)





Moustakas, K. et al. (2017)
Erdemir A., “Open Knee: Open Source Modeling and Simulation in Knee Biomechanics”. Computational Biomodeling (CoBi) Core and Department of Biomedical Engineering, Cleveland Clinic, Cleveland, Ohio, Thieme Medical Publishers 333 Seventh Avenue, New York, NY 10001, USA, October 7, 2015.

Why is the problem of ACL prevention not solved?

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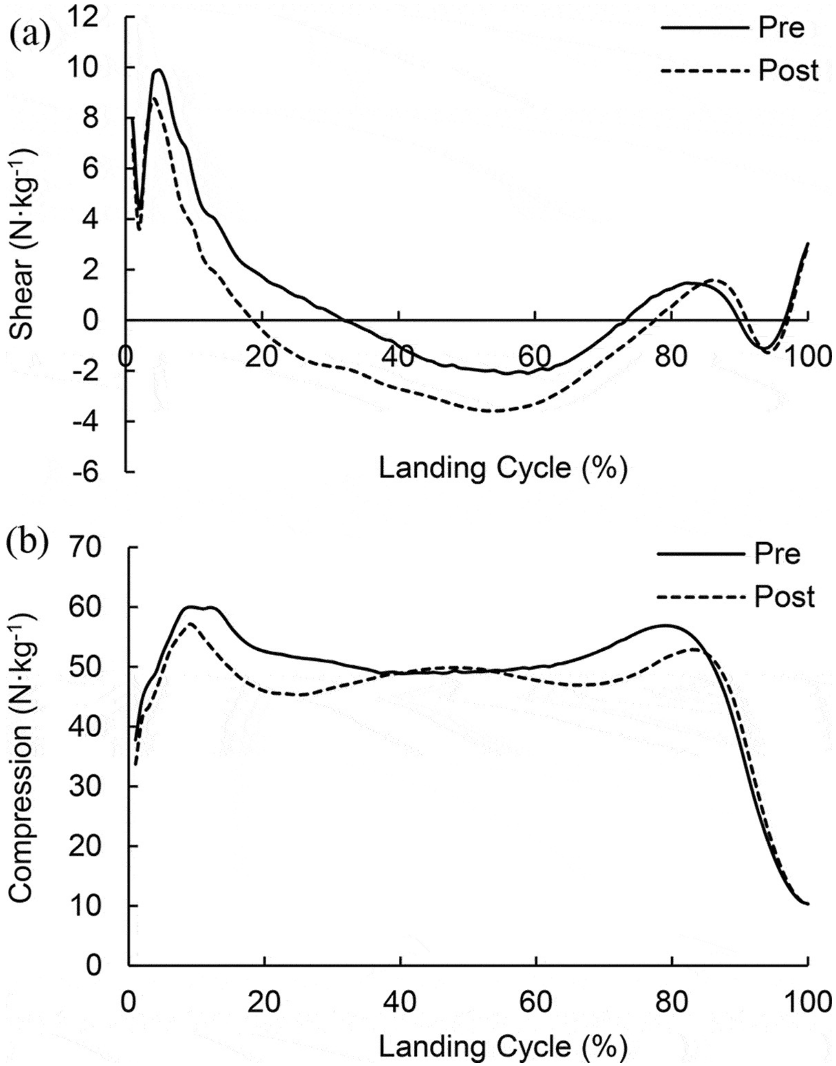
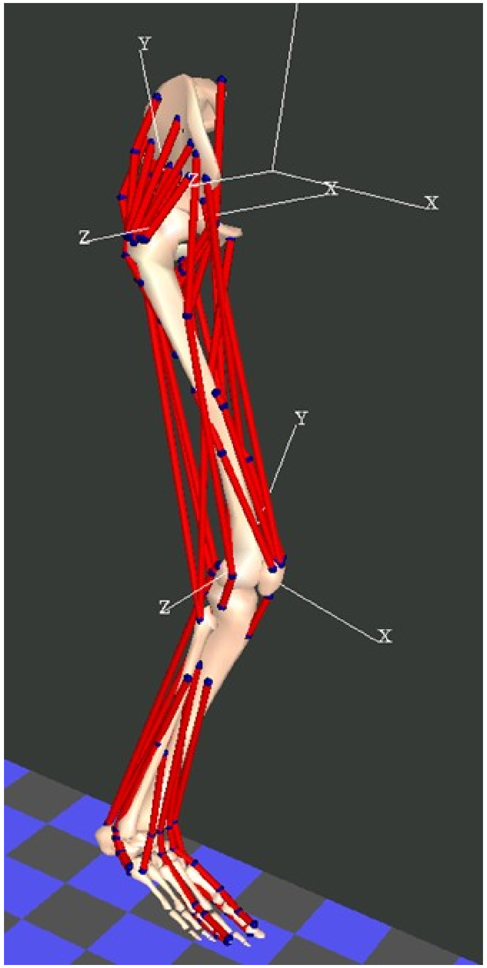
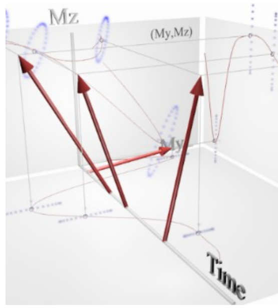




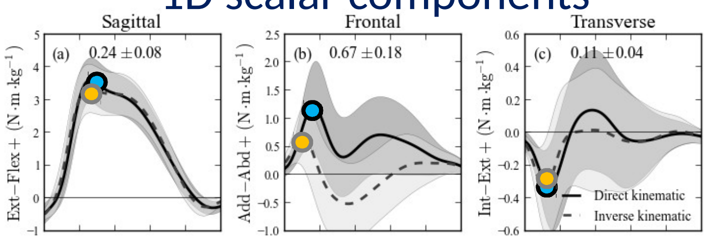
Liang-Ching Tsai, Yi-An Ko, Kyle E. Hammond, John W. Xerogeanes, Gordon L. Warren & Christopher M. Powers (2017) Increasing hip and knee flexion during a drop-jump task reduces tibiofemoral shear and compressive forces: implications for ACL injury prevention training, Journal of Sports Sciences, 35:24, 2405-2411, DOI: 10.1080/02640414.2016.1271138

Problem with single variables

1D vector



1D scalar components



0D peaks

Sagittal	Frontal	Transverse
3.2	0.7	0.31

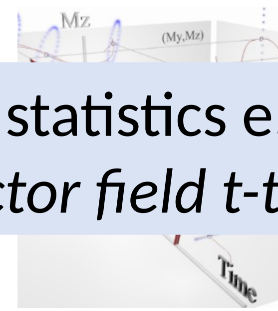
0D statistics e.g. *t*-test

Solution

Statistical Parametric Mapping

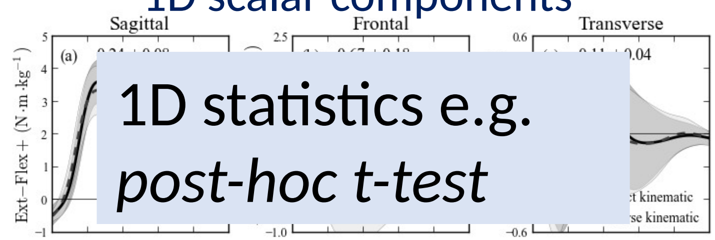
www.spm1d.org

1D vector



1D statistics e.g.
vector field t-test

1D scalar components



1D statistics e.g.
post-hoc t-test

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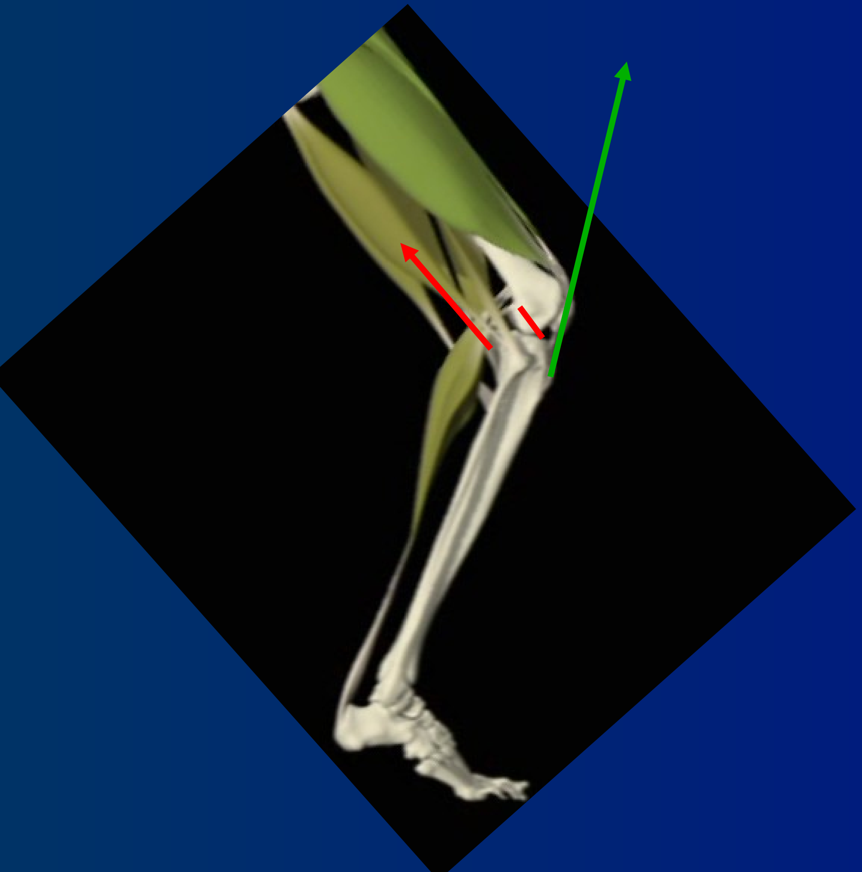
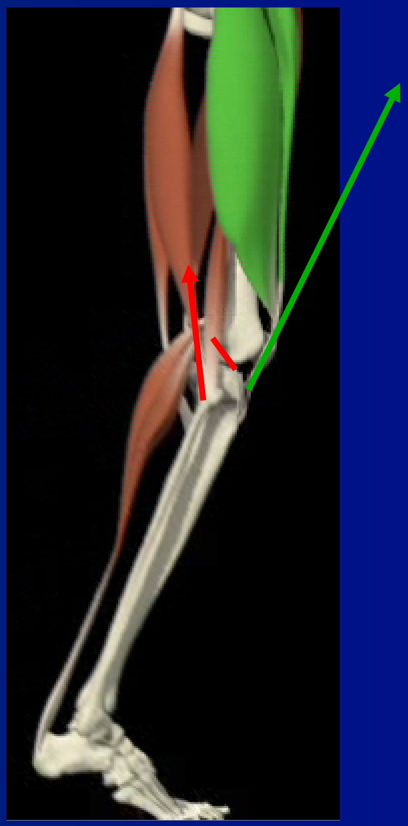
3. **The biomechanics of the knee joint and ACL mechanics change in-vivo during movement**

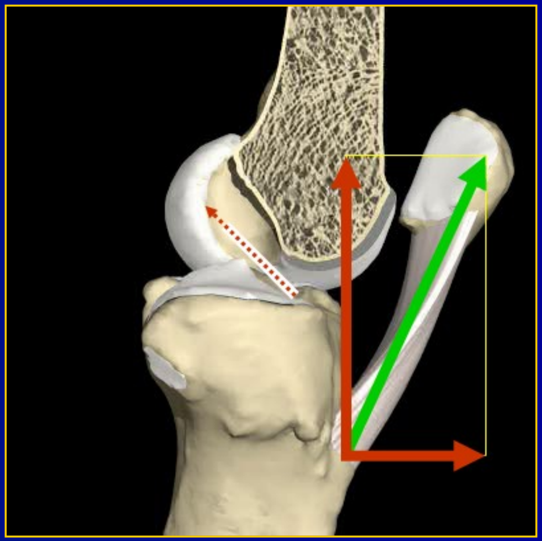
ACL Injury Risk Factors

Landing/Pivoting with knee extended:

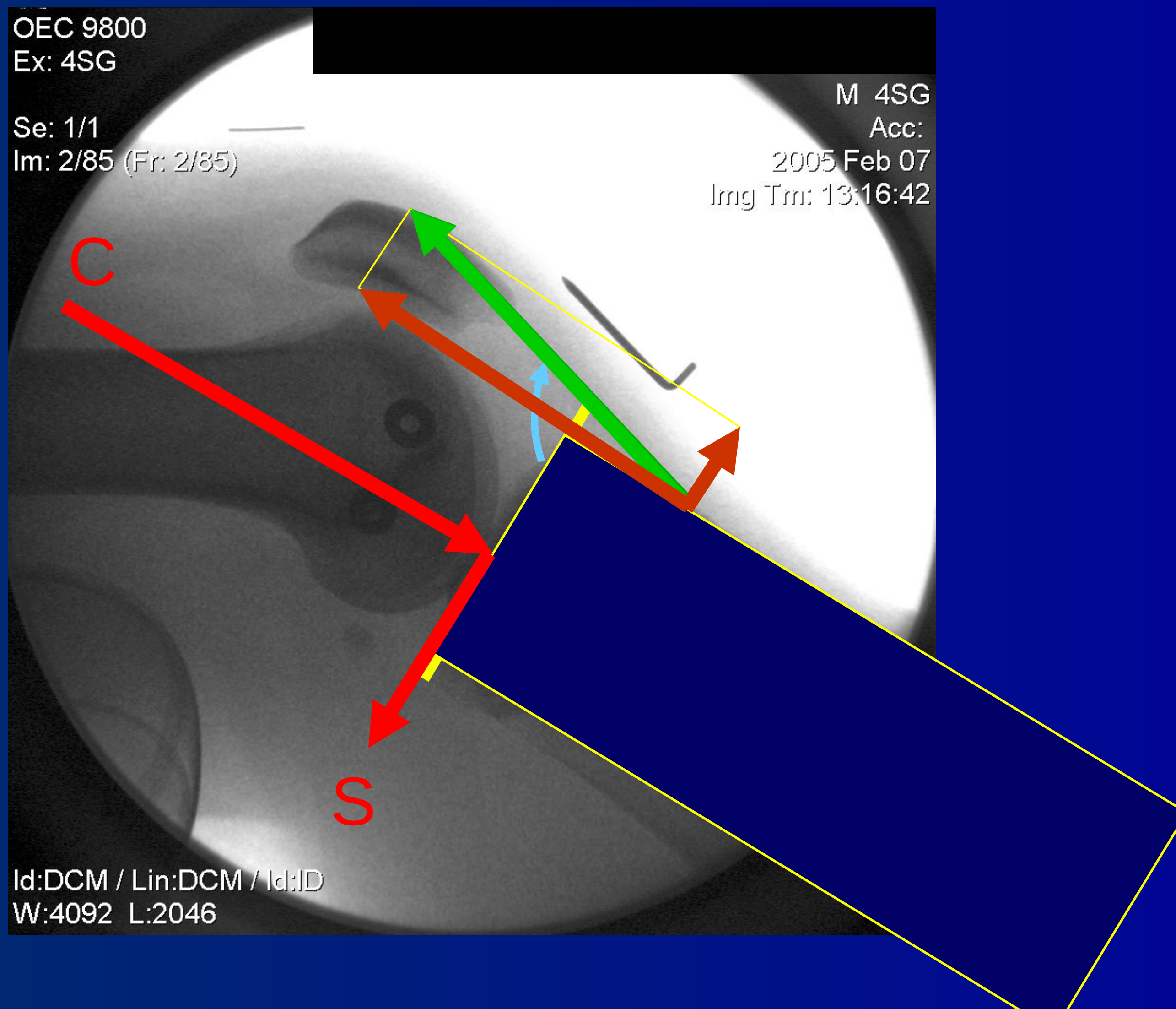
- Patellar Tendon Shear Load Higher
- Hamstring Co-activation less effective in protecting ACL



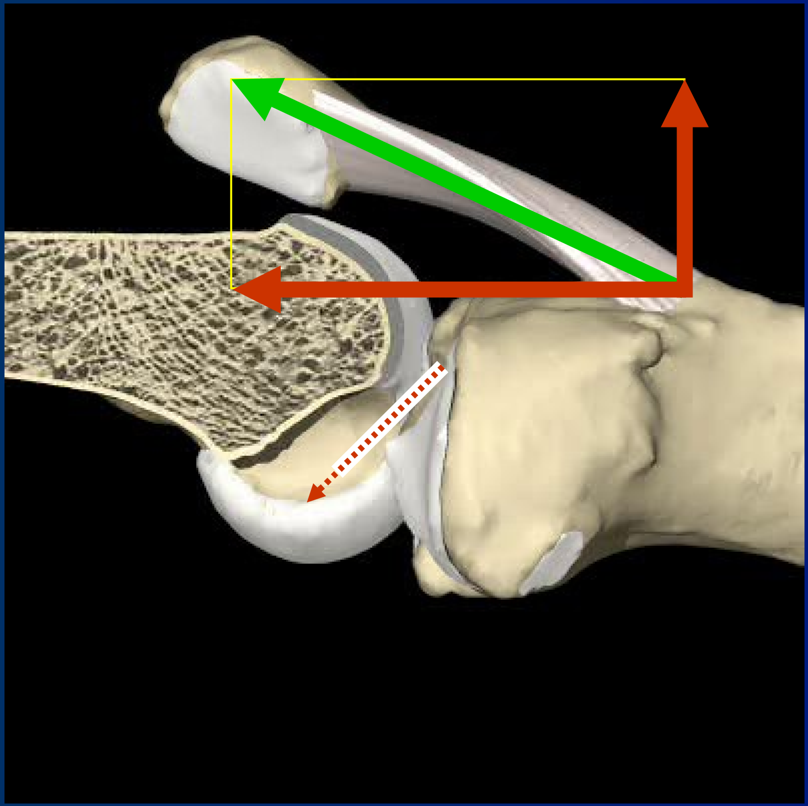




The orientation of tendon (angle relative to articular surface) determines joint forces (compressive and shear)

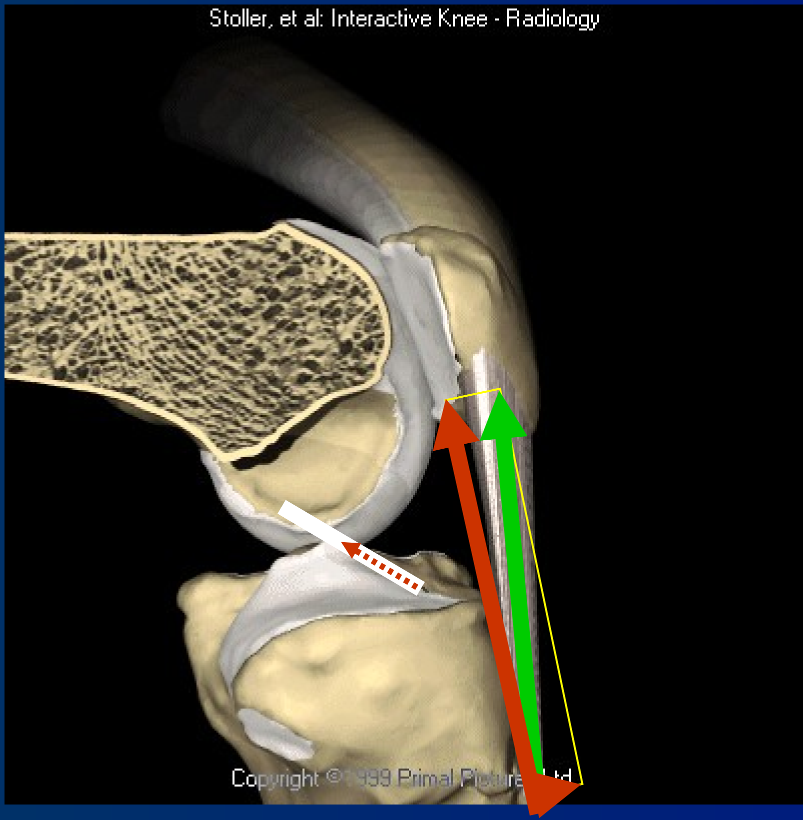


Shear Component of PT Force: Loading of ACL implications



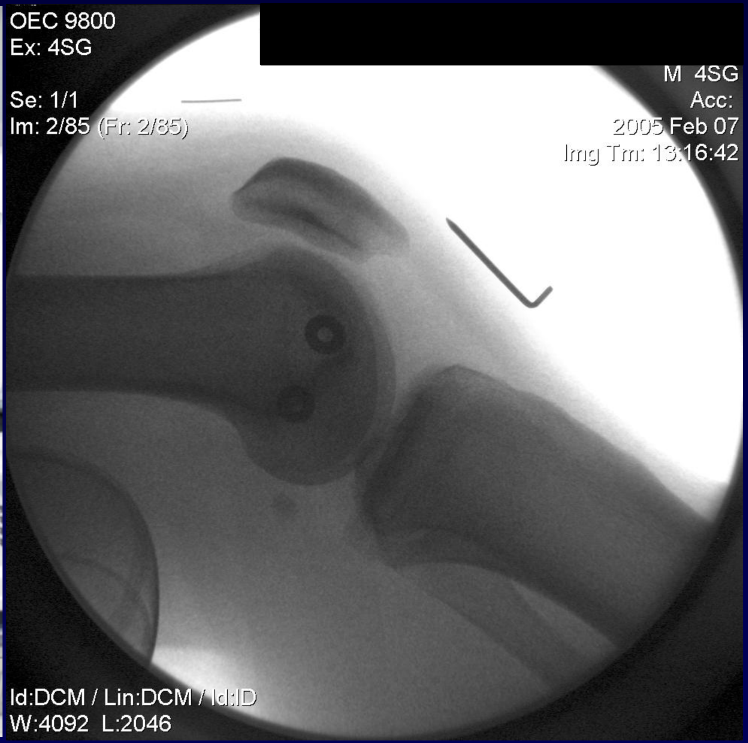
- Patellar Tendon angle with Tibial plateau ~ 112 deg when the knee is near full extension
- Patellar Tendon Force shear component large near full knee extension
- Large loading on ACL

Shear Component of PT Force: Loading of ACL implications

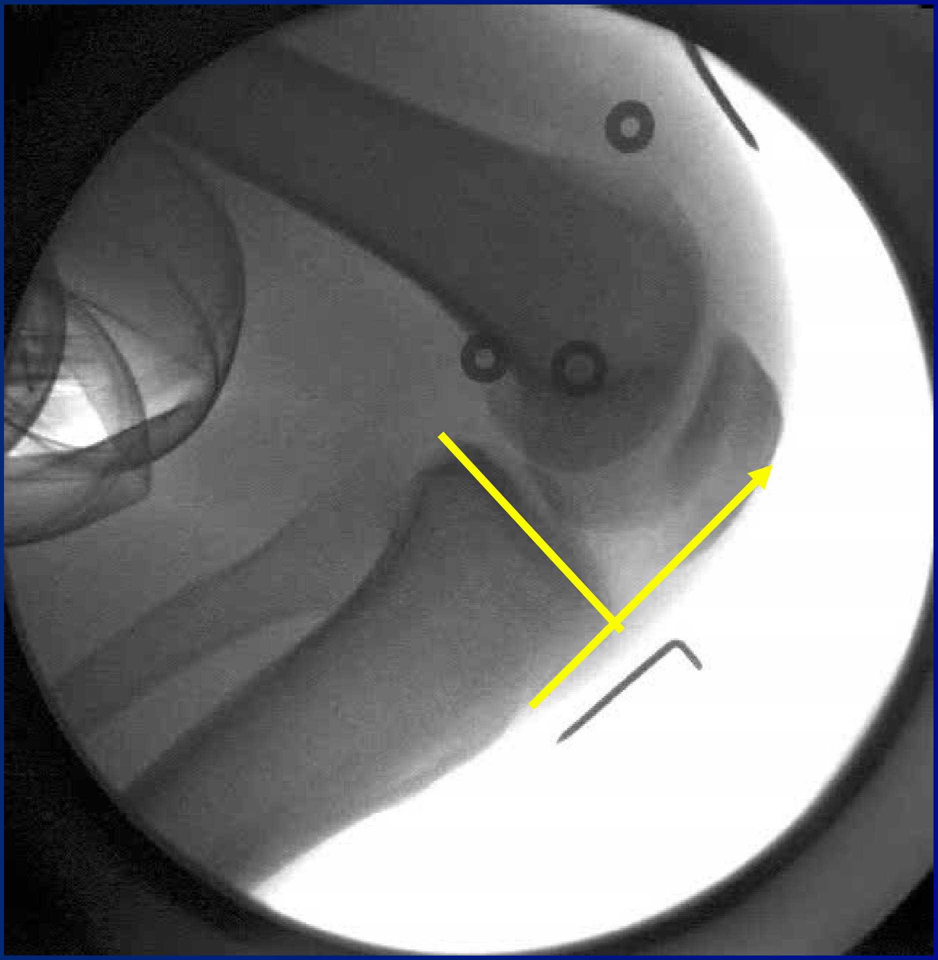


- Patellar Tendon angle with Tibial plateau ~ 90 deg when the knee is at 90 deg of knee flexion
- Patellar Tendon Force shear component less at flexed knee positions
- Less loading on ACL

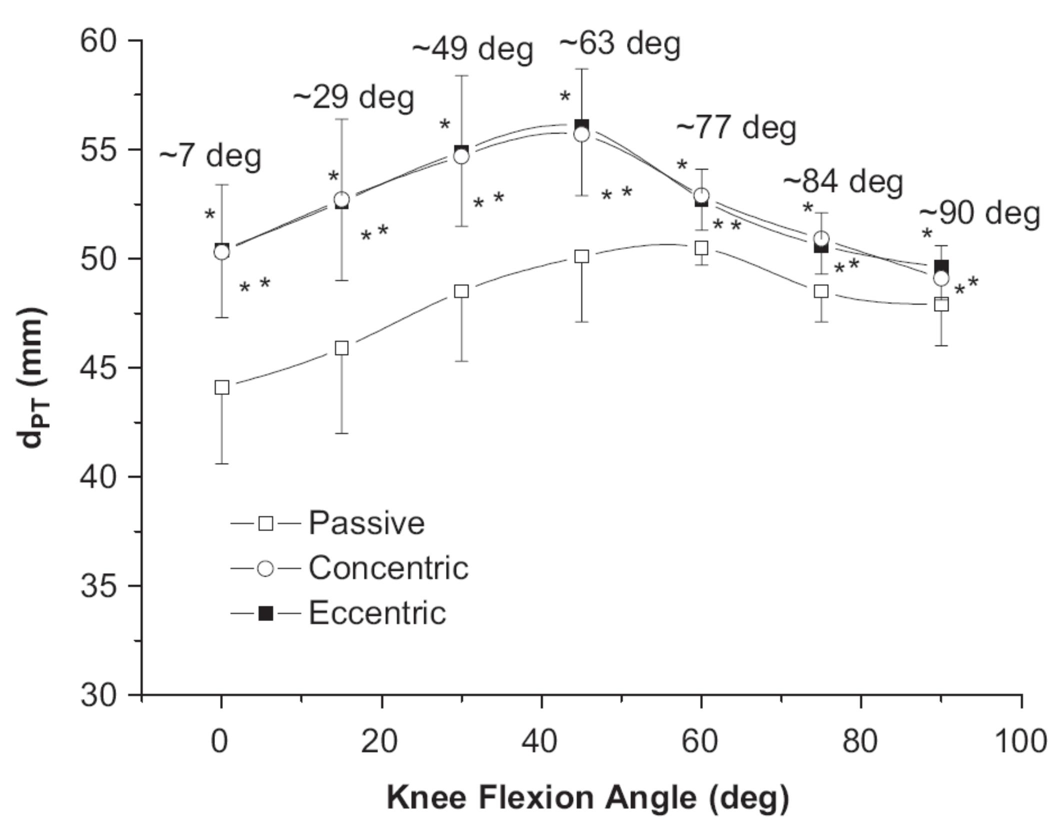
Measurement of knee joint kinematics <u>during contraction</u> using X-Ray video fluoroscopy



Isokinetic Concentric Knee Extension
60 ^{o}/sec

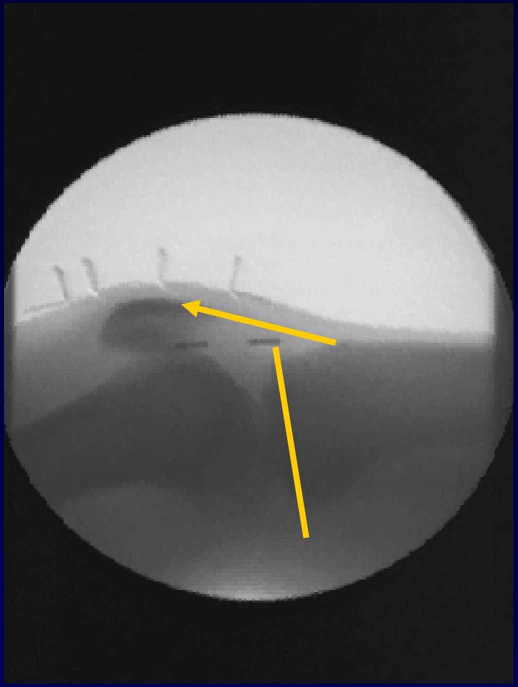


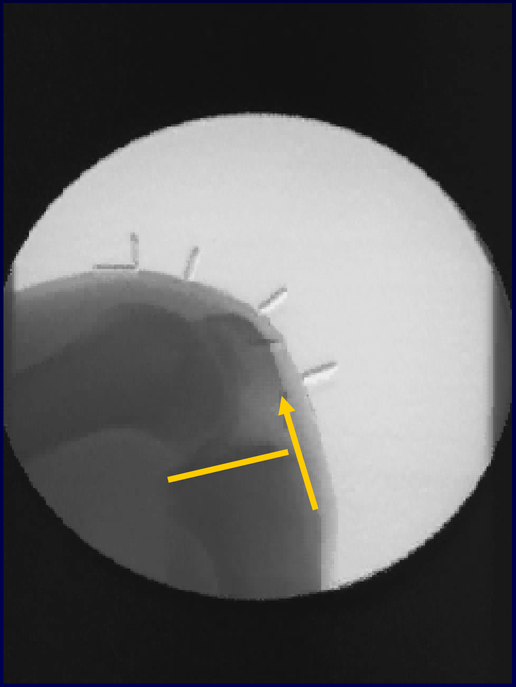
Effects of contraction on patellar tendon moment arm

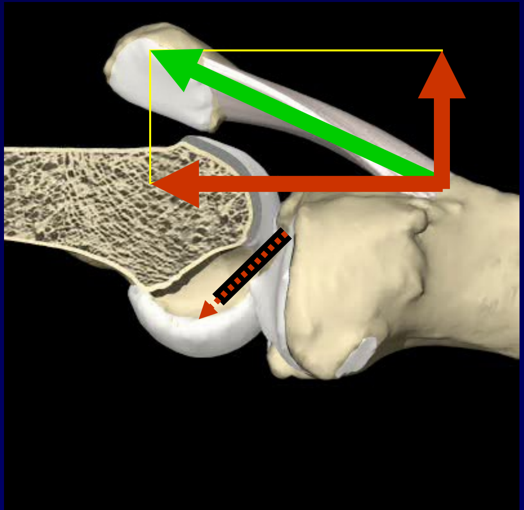


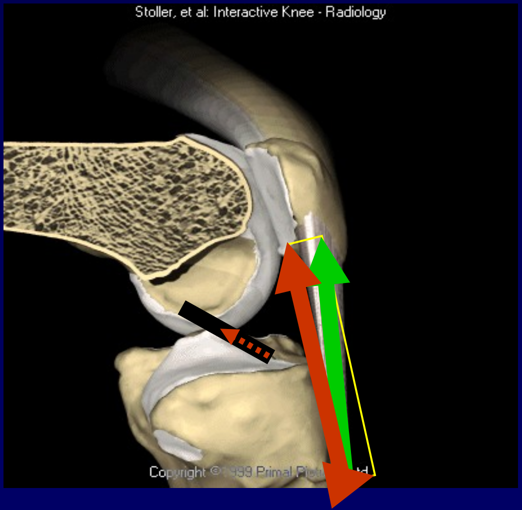
Tsaopoulos, Baltzopoulos, Richards & Maganaris, (2007), Journal of Biomechanics, 40, 3325–3332

Orientation of patellar tendon relative to tibial plateau and implications for joint loading

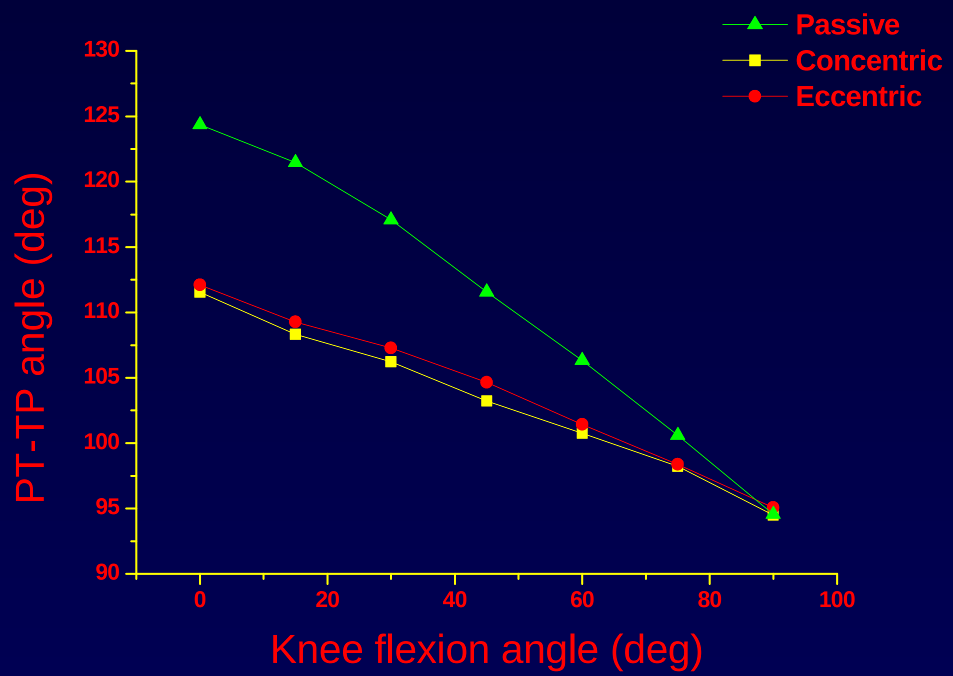


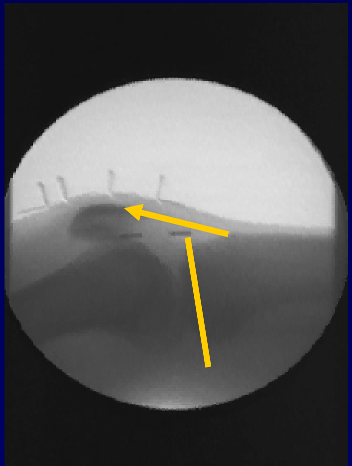


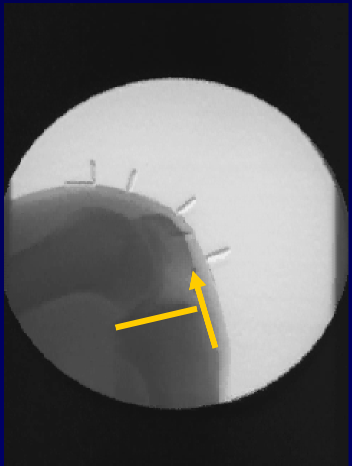




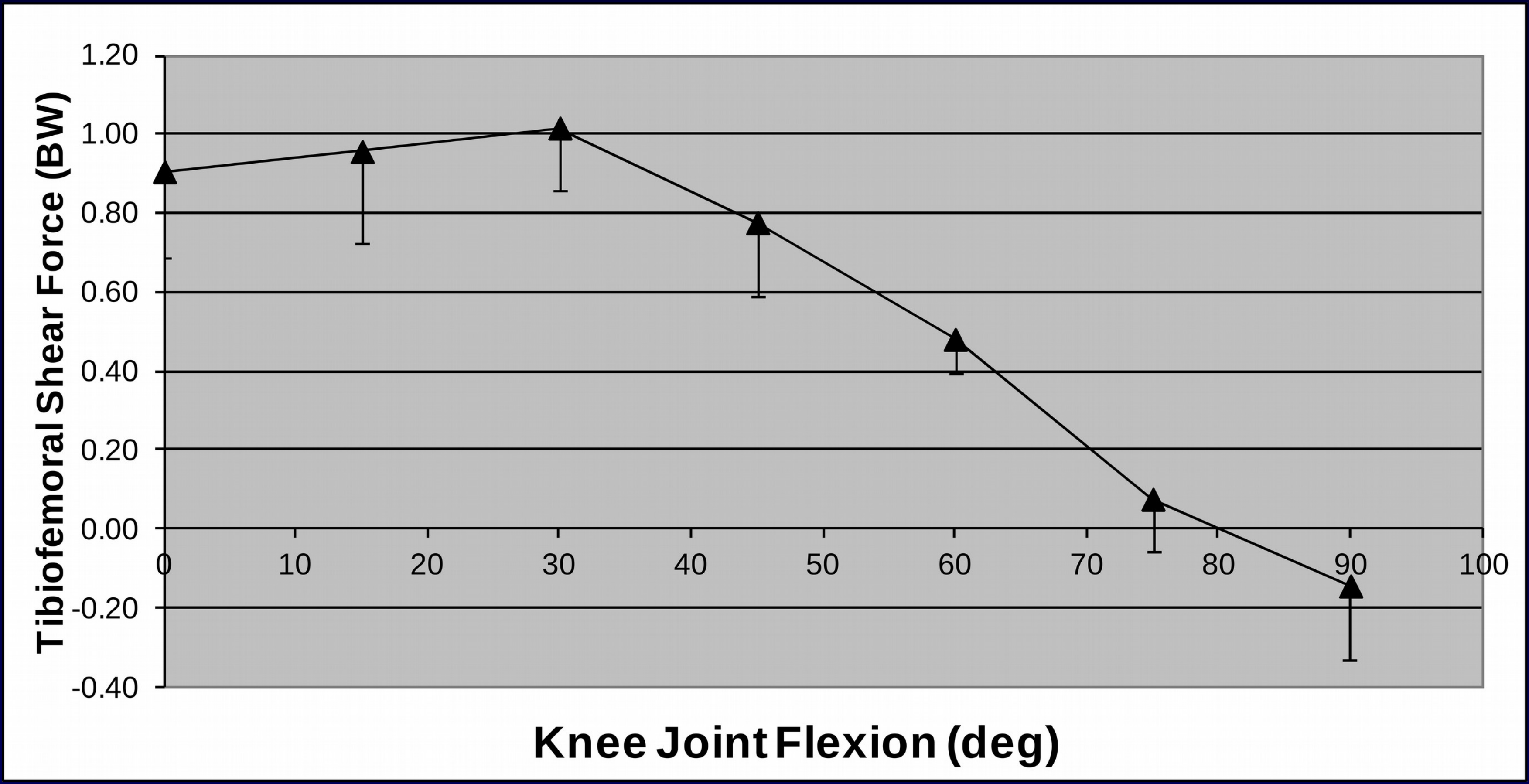
Effects of contraction mode on patellar tendon orientation



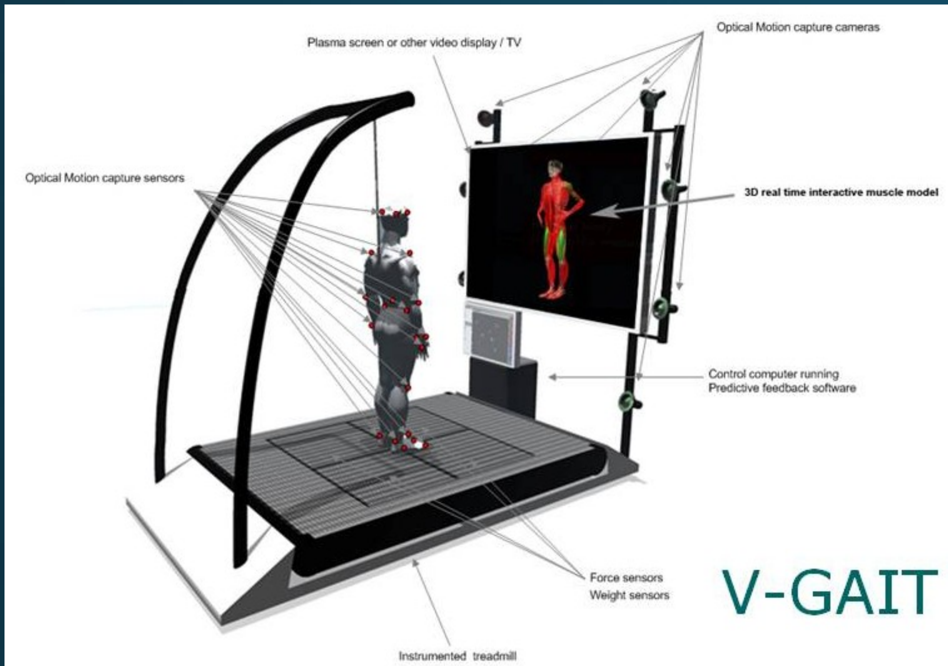




Tibiofemoral shear force during concentric knee extension and ACL Loading



Loading higher in extended knee joint positions

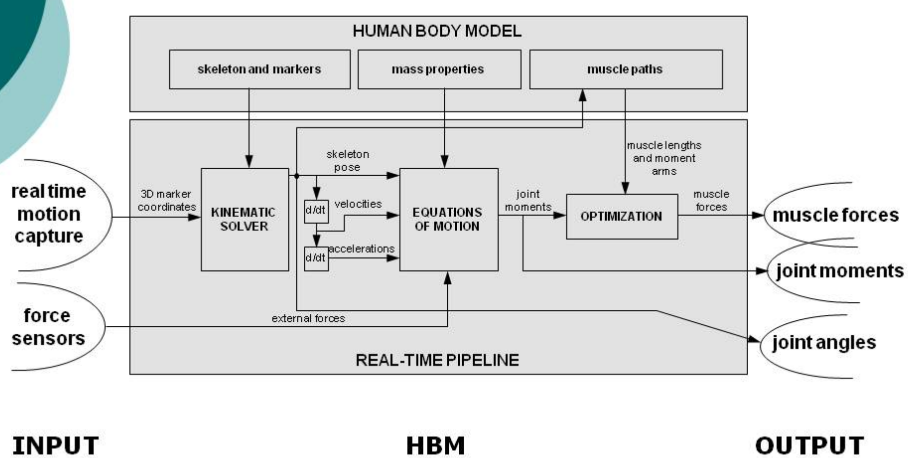


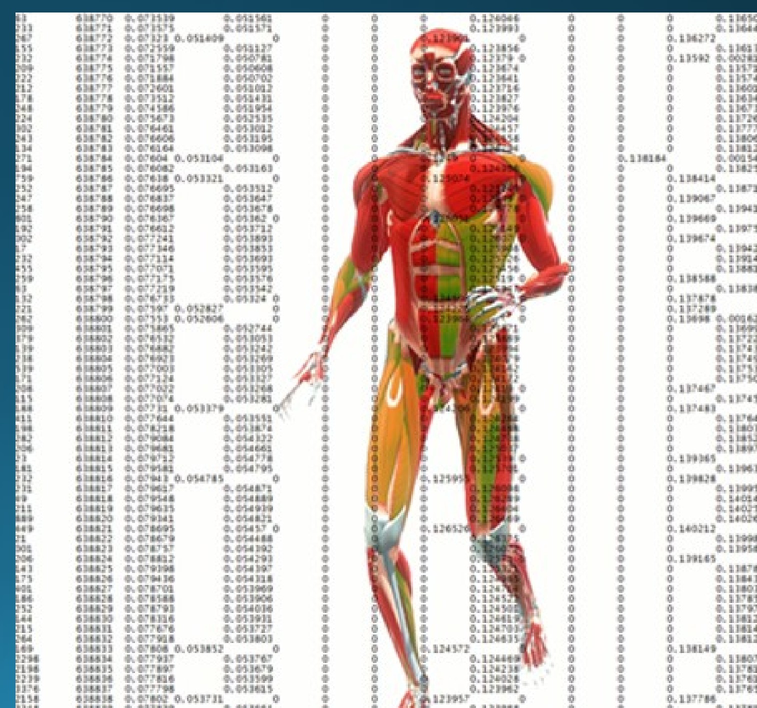
Human Body Model (HBM) and Real-Time Movement Analysis

Ton van den Bogert
Cleveland Clinic, Ohio

Oshri Even-Zohar
Thomas Geijtenbeek
Motek Medical B.V., Amsterdam

Flowchart





Estimation of muscle forces

Available online at www.sciencedirect.com

ScienceDirect

Clinical Biomechanics 22 (2007) 131–154

CLINICAL BIOMECHANICS

www.elsevier.com/locate/clinbiomech

ELSEVIER

Review

Model-based estimation of muscle forces exerted during movements

Ahmet Erdemir [a], Scott McLean [a], Walter Herzog [b], Antonie J. van den Bogert [a,*]

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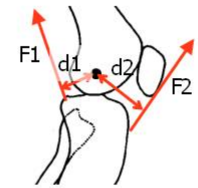
Received 18 October 2005; accepted 8 September 2006

Estimation of muscle forces

- Joint moment represents total action of all muscles across joint
  - Moment = -F1 x d1 + F2 x d2

force

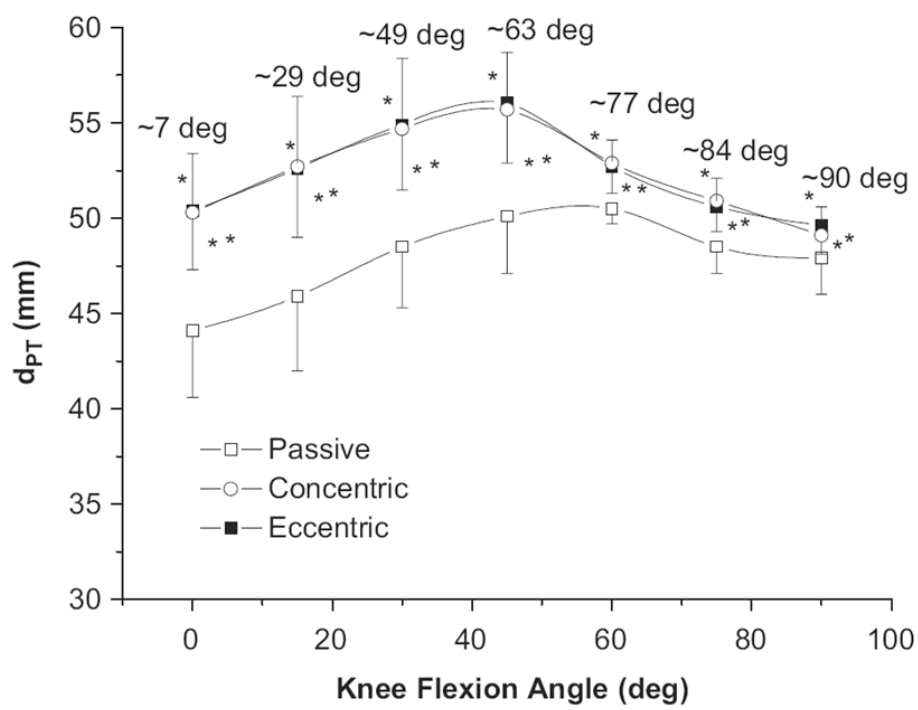
moment arm (lever arm)



- More unknowns (muscles) than equations
- Therefore, search for the "optimal" solution
- Applied in research on orthopedic devices
- Not commonly used in clinical gait analysis

Muscle moment arms change dynamically during contraction and are dependent on the conditions and joint kinematics

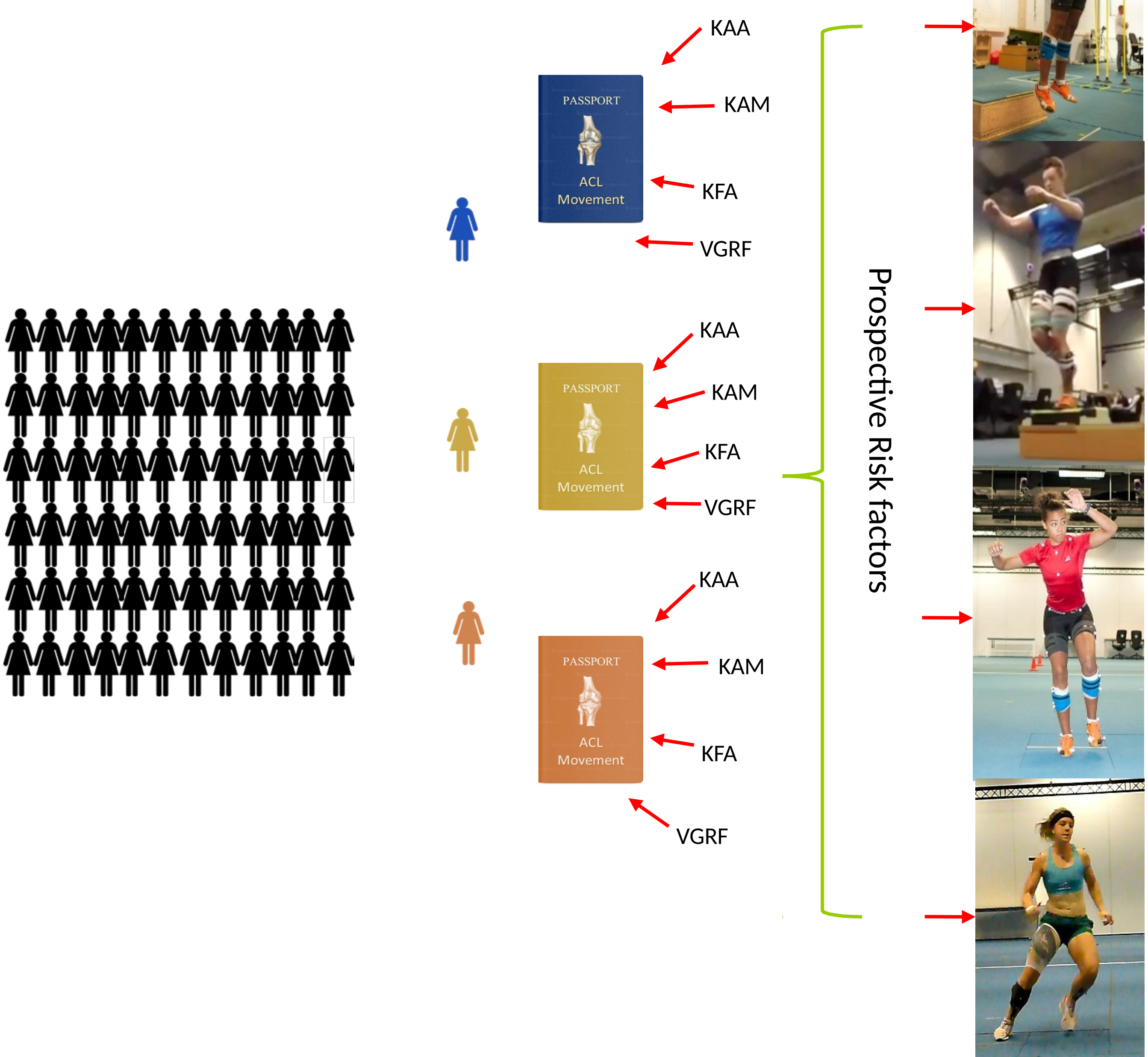
Tsaopoulos, Baltzopoulos, Richards & Maganaris, (2007), Journal of



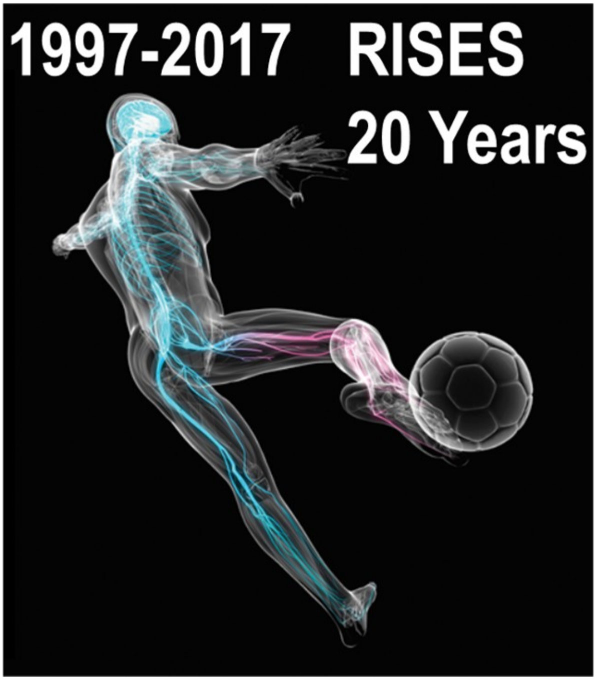
Challenges of screening for ACL injury risk
What are the known risk factors?

Biomechanical risk factors

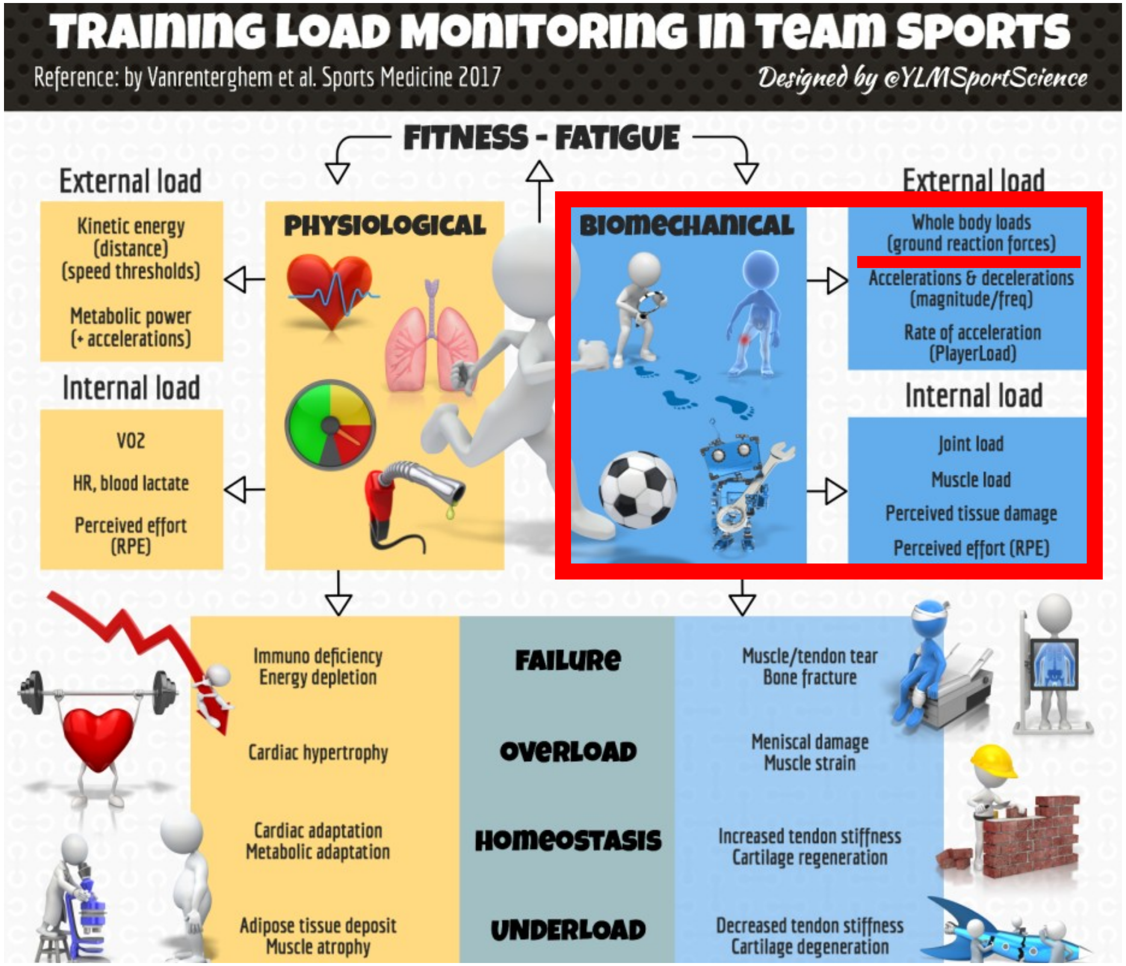
Screening for ACL injury risk: The Liverpool Knee Study & the ACL Movement Passport



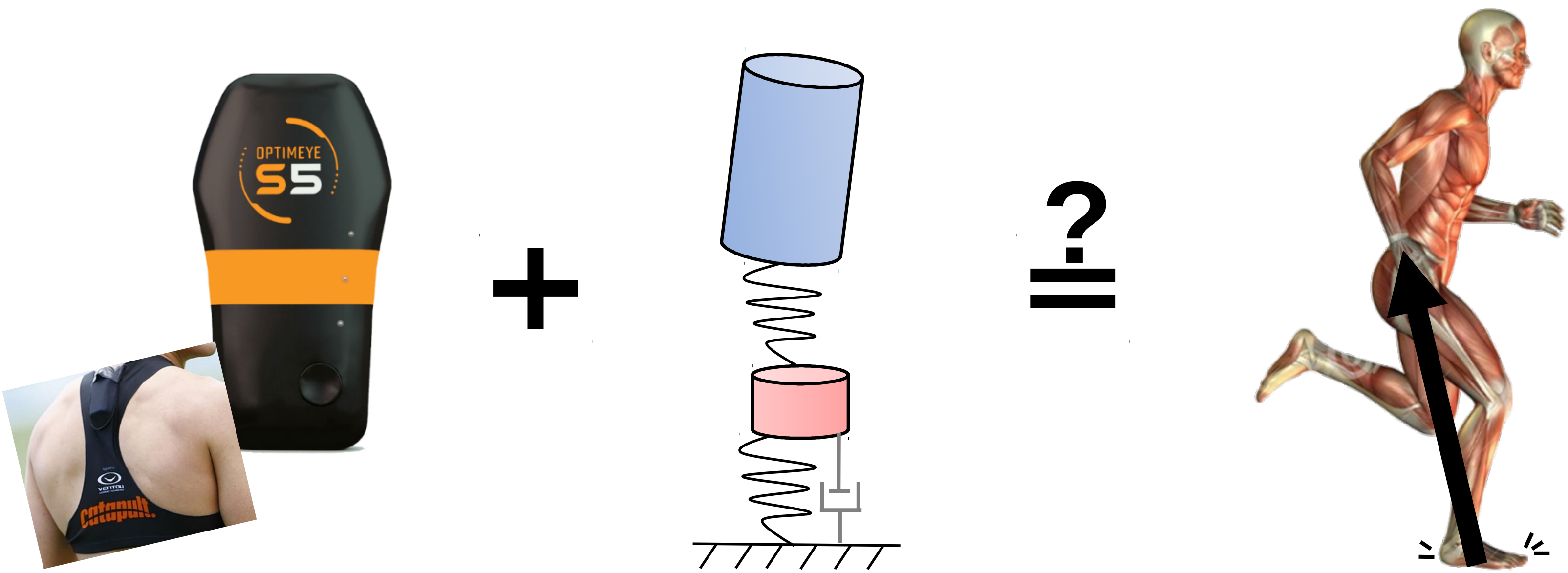
LIVERPOOL JOHN MOORES UNIVERSITY

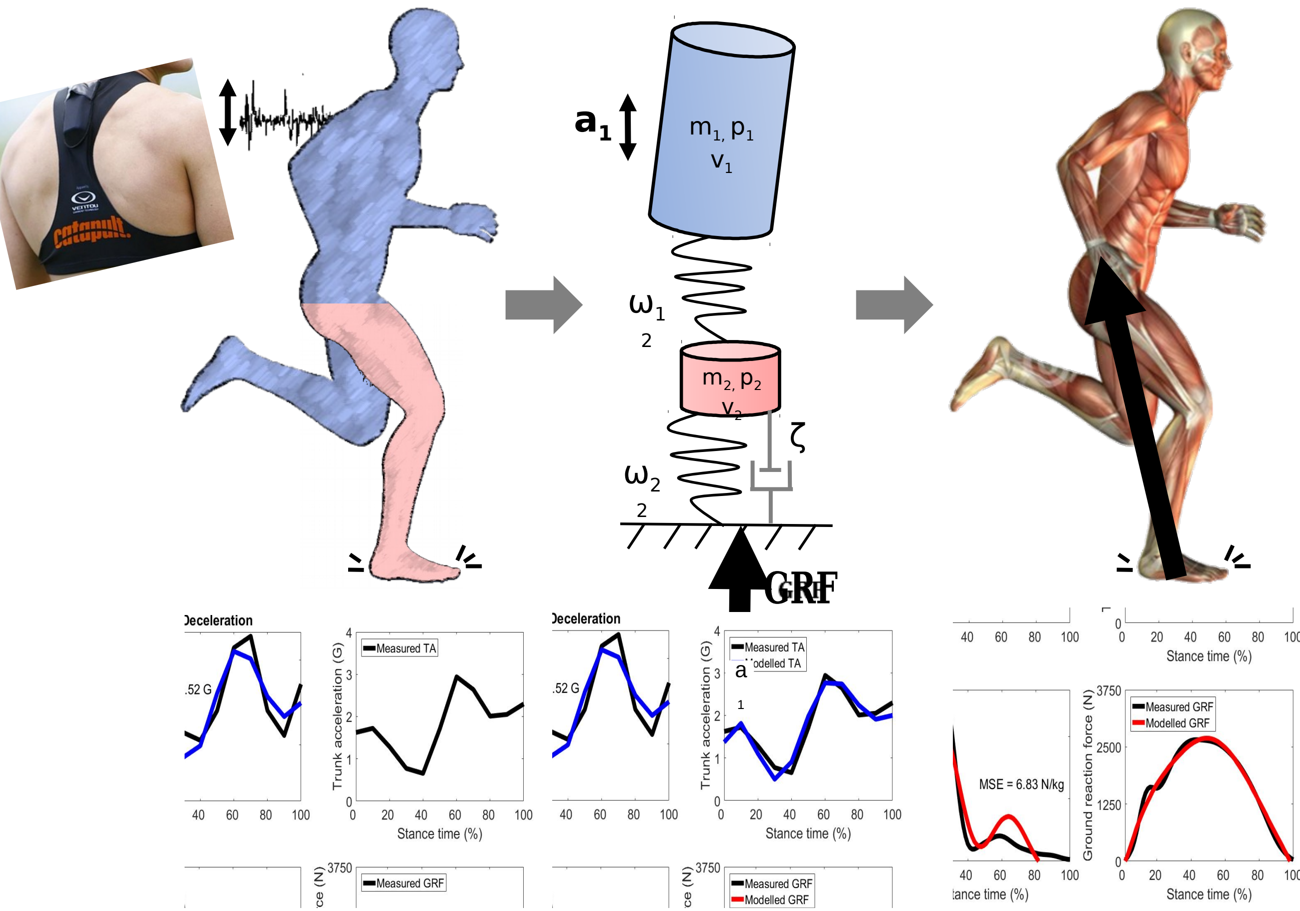


Σας Ευχαριστώ Πολύ


TRAINING LOAD MONITORING IN TEAM SPORTS
Reference: by Vanrenterghem et al. Sports Medicine 2017
Designed by @YLMSportScience
FITNESS - FATIGUE
External load
Kinetic energy (distance) (speed thresholds)
Metabolic power (+ accelerations)
Internal load
VO2
HR, blood lactate
Perceived effort (RPE)
PHYSIOLOGICAL
BIOMECHANICAL
External load
Whole body loads (ground reaction forces)
Accelerations & decelerations (magnitude/freq)
Rate of acceleration (PlayerLoad)
Internal load
Joint load
Muscle load
Perceived tissue damage
Perceived effort (RPE)
Immuno deficiency
Energy depletion
Cardiac hypertrophy
Cardiac adaptation
Metabolic adaptation
Adipose tissue deposit
Muscle atrophy
FAILURE
OVERLOAD
HOMEOSTASIS
UNDERLOAD
Muscle/tendon tear
Bone fracture
Meniscal damage
Muscle strain
Increased tendon stiffness
Cartilage regeneration
Decreased tendon stiffness
Cartilage degeneration

Can field measured trunk accelerations predict GRF





1: Measure trunk acceleration

Measure accelerations of the upper trunk with a body-worn accelerometer

2: Fit model to trunk acceleration

Adjust model parameters to fit upper mass acceleration to measured trunk acceleration via numerical optimization

$$\mathbf{a_1} = -\omega_1^2 (p_1 - p_2) + g$$

3: Calculate ground reaction force

Calculate GRF from the eight model parameters

$$\mathbf{GRF} = \frac{M\omega_2}{1+\lambda}\lambda(\omega_2 p_2 + 2\zeta v_2)$$

Anterior Cruciate Ligament

- Cruciate ligaments: Named anterior and posterior with regard to the positions of their attachments on the tibial plateau;
- Anterior cruciate ligament attached to the anterior intercondylar area of the tibial plateau,
- Cruciate ligaments because they cross each other (like the limbs of the letter X).
- Both cruciate ligaments are situated within the capsule of the knee joint. However they are not within the synovial cavity of the knee joint.
- Sensory innervation from the genicular branches of the tibial, common peroneal and obturator nerves. Sensations subserved by these sensory nerves include both pain and proprioception, and correspondingly both pain receptors and mechano-receptors have been identified within the cruciate ligaments.
- The cruciate ligaments are vascularized structures; the blood supply of the cruciate ligaments being derived from the genicular branches (principally the middle genicular branch) of the popliteal artery. Thus hemarthrosis is an important clinical feature of cruciate rupture.

Results of Anterior Cruciate Ligament Reconstruction With Patellar Tendon Autografts: Objective Factors Associated With the Development of Osteoarthritis at 20 to 33 Years After Surgery

TABLE 7
Binary Logistic Regression Analysis of Statistically Significant Factors Related to the Presence of Osteoarthritis on Radiographs at >20 Years' Follow-up

Variable	Coefficient	Standard Error	*P* Value	Odds Ratio (95% CI)
Medial meniscus removed	0.5366	0.1194	<.0001	2.9 (1.8-4.7)
Knee extension less than normal at discharge[a]	0.3637	0.1609	.024	2.1 (1.1-3.9)
Older age at surgery	0.0379	0.01478	.011	1.04 (1.0-1.07)

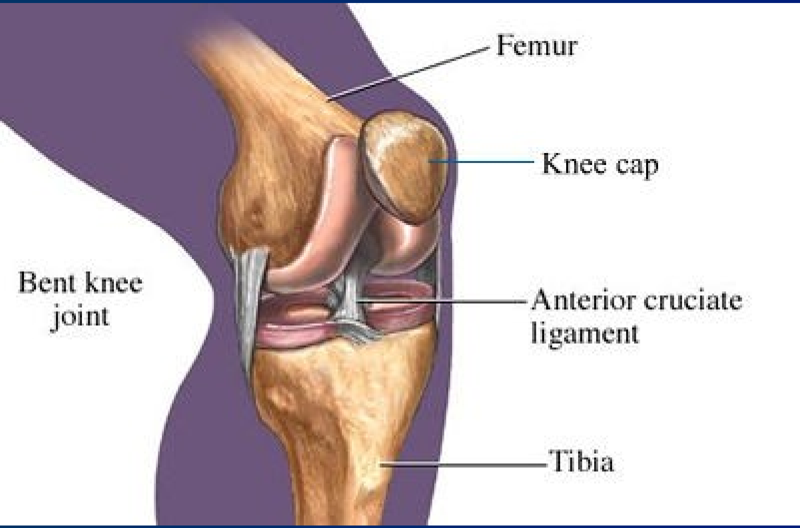
[a]Knee extension less than normal (within 2° of opposite knee) at the time of discharge from physical therapy treatment.

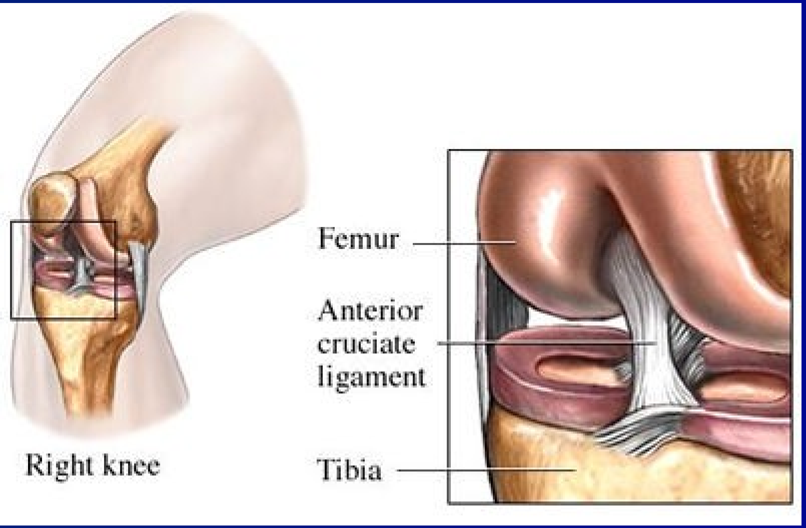
Table 7 Binary Logistic Regression Analysis of Statistically Significant Factors Related to the Presence of Osteoarthritis on Radiographs at >20 Years' Follow-up

Published in: K. Donald Shelbourne; Rodney W. Benner; Tinker Gray; *Am J Sports Med* 45, 2730-2738.
DOI: 10.1177/0363546517718827

Biomechanics of ACL

- MAINTAINING ANATOMIC ALIGNMENT
- TRANSMITTING LOAD BETWEEN FEMUR & TIBIA
- GUIDING JOINT MOTION





Injury Prevention

Specific strategies for injury prevention:

- Identification of risk factors
- Training programs to modify risk factors (related to technique, strength, balance, neuromuscular function, proprioception etc)
- Rules changes
- Shoe/playing surface interface
- Equipment/Bracing

ACL Injury Prevention
Training Programs

- **Sportmetrics (Neuromuscular Training)**
  - Hewett et al. (1999), Am J Sports Med
  - Cinicinnati Sportsmedicine Research and Education Foundation

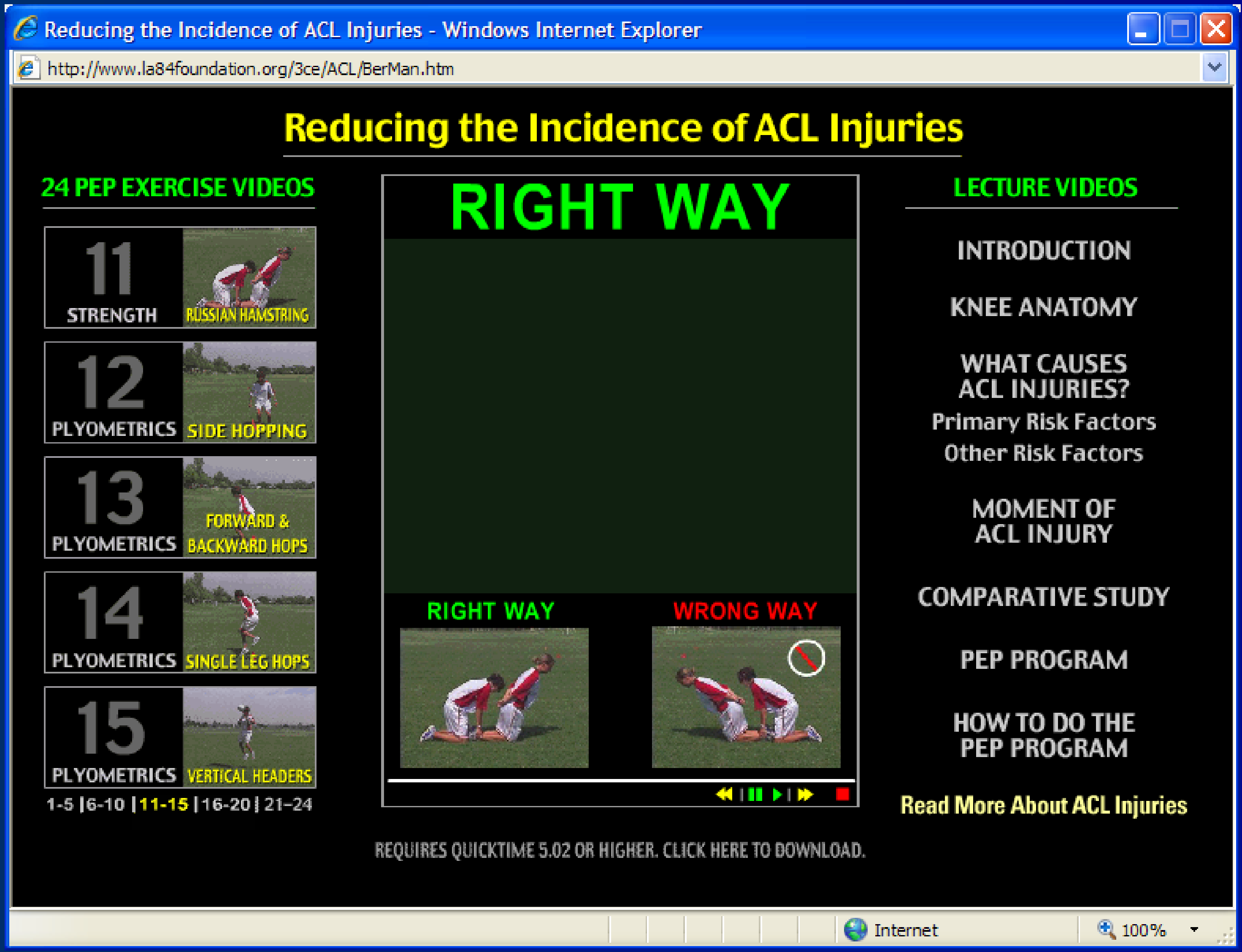
- **PEP** (Prevent injury Enhance Performance)
  - Mandelbaum et al. (2005), Am J Sports Med
  - Santa Monica Orthopedic and Sports Medicine Research Foundation

ACL Injury Prevention
Training Programs

- Sportmetrics
  - 6 week Preseason-training program
  - 60 – 90 minute work-out

- PEP
  - 15 minute work-out
  - Use in place of usual pre-practice warm-up 3 d/wk

PEP (Prevent injury Enhance Performance)



PEP (Prevent injury Enhance Performance)

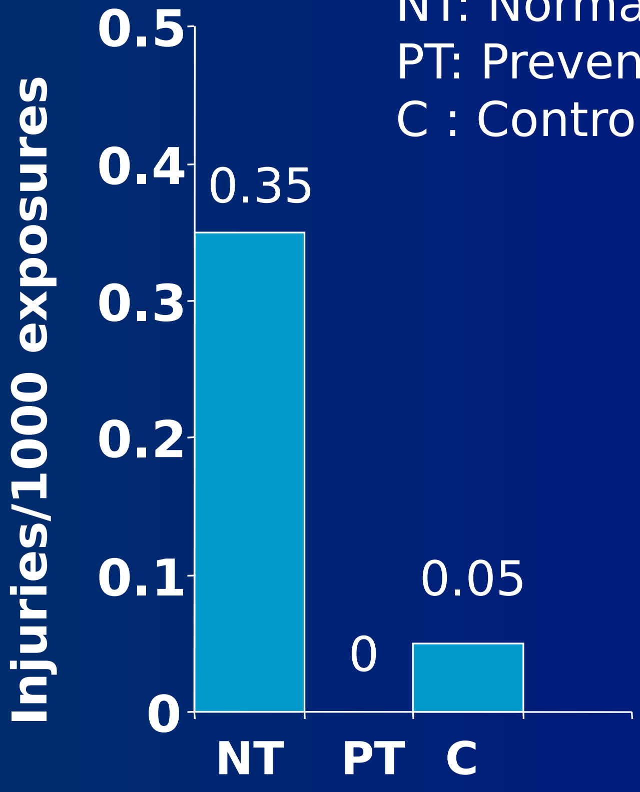
ACL Injury Prevention
Training Program Main Goals

- Emphasize proper landing techniques
  - Land on balls of feet and absorb impact
    - Soft landing
    - Toe-to-heel rocking of the foot
      - ↓ ground reactive forces
  - Knees flexed
  - Prevent knee valgus on landing
  - Balance during landing: chest over knees

Effects of Training Programs:

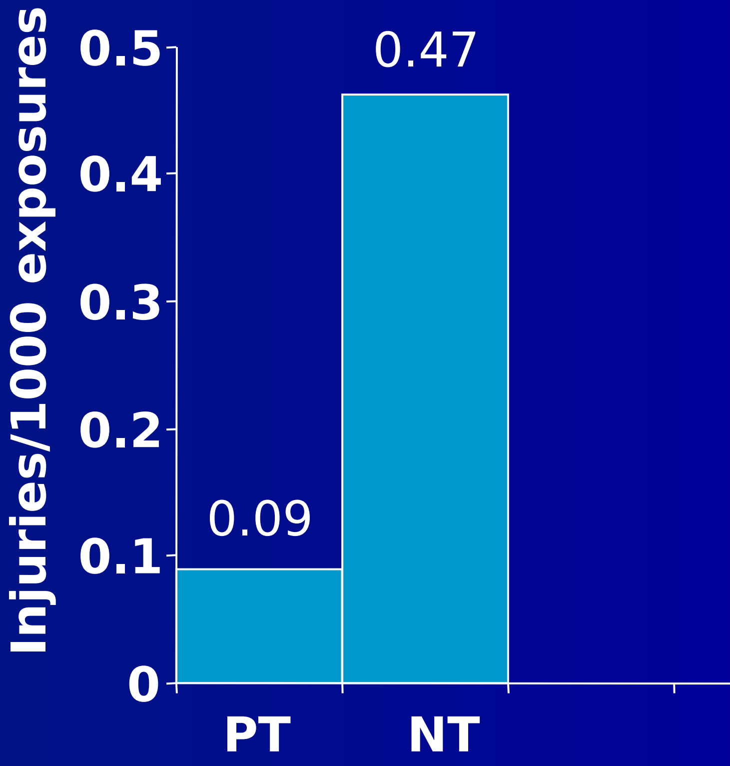
Reduction in non-contact injuries in trained groups

NT: Normal Training
PT: Prevention Training
C : Control (Males)



Sportsmetrics

Hewett et al. (1999) AJSM



PEP

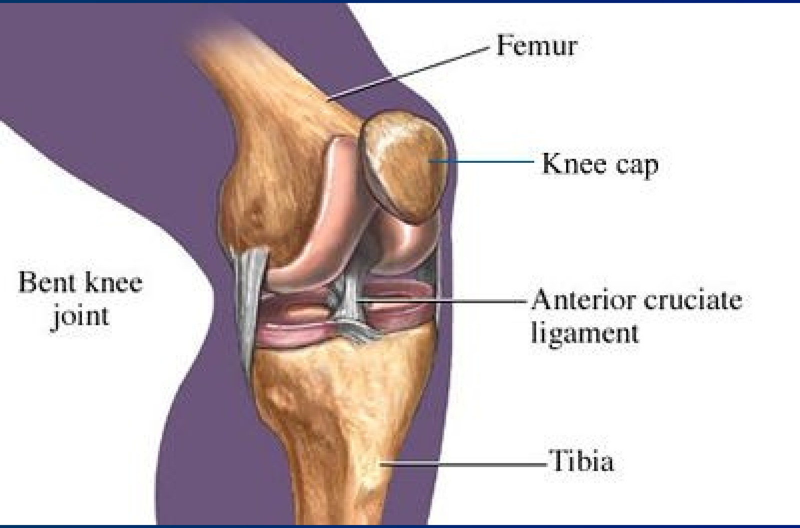
Mandelbaum et al. (2005) AJSM

Anterior Cruciate Ligament (ACL)

- Anatomy
- Biomechanics
- Mechanisms of Injury
- Prevention

Biomechanics of ACL

Function of the anterior cruciate ligament



- Primary restraint to anterior translation of the tibia and contributes the most at 30° flexion.
- Prevents hyperextension of the knee
- Secondary restraint to internal tibial rotation, a secondary restraint to adduction and abduction at full extension
- ‘Guides' the screw home rotation of the knee joint as it approaches terminal extension.

ACL Injuries: Aetiology

- Injuries to the anterior cruciate ligament are fairly common in a wide range of sports
- Injuries can be either contact or non-contact
- Non-contact ACL injuries typically occur when decelerating, landing after a jump, twisting, or cutting activities. Contact injuries usually result from a valgus force to a planted foot.
- ACL injuries are usually associated with damage to other structures such as collateral ligaments or menisci. Isolated contact ACL injuries are rare. Most injuries occur in Closed Kinetic Chain
- Anterior cruciate ligament rupture usually results from a severe rotary strain to the knee. This frequently occurs in skiing sports and in contact games such as soccer or rugby/football
- The incidence of ACL injuries is much more common in females than males. This may be due to gender anatomical differences, such as an increased Q-angle and a narrower intercondylar notch.

ACL Injuries

- Most common mechanisms
  - Contact:
    - **CKC with foot rotated with valgus stress**
    - **Hyperextension**
    - **direct hit on the posterior tibia**
  - Non-Contact:
    - **Most common**
    - **Due to sudden deceleration**

- Patient will experience “buckling” or “giving away”, typically will hear and/or feel a “pop” which is actually the tearing of the ligament tissue, followed by soft tissue swelling, pain and disability

Non-contact mechanism of injury usually involving:

- **Planting and cutting -** the foot is positioned firmly on the ground followed by the leg (and body for that matter) turning one direction or the other. **Example**: Football player making a fast cut and changing direction.
- **Straight-knee landing -** results when the foot strikes the ground with the knee straight. **Example**: Basketball or Netball player coming down after a jump shot or a gymnast landing.
- **One-step-stop landing with the knee hyperextended -** results when the leg abruptly stops while in an over-straightened position. **Example**: Player sliding with the knee hyperextended with additional force upon hyperextension.
- **Pivoting and sudden deceleration** resulting from a combination of rapid slowing down and a plant and twist of the foot placing extreme rotation at the knee. **Example**: Football player quickly slowing down followed by a quick turn in direction.

ACL Injuries

Often combined with other injuries to the knee including injuries to the medial collateral ligament (MCL) and the medial meniscus (MM)

- **O’Donoghue’s triad:**
- – ACL tear
- – MCL complete disruption
- – Peripheral MM tear

Location:

- – Midsubstance - 70%
- – proximal - 20%
- – distal - 10%

ACL – MAIN MECHANISMS OF INJURY

1. “ SCREWING HOME” TIBIA OVER FEMUR BY EXT.ROTATE TIBIA WHEN KNEE EXTENDS
2. RESISTING ANTERIOR DISPLACEMENT OF THE TIBIA ON THE FEMUR (SKI)
3. EXCESSIVE EXT.ROTATION OF TIBIA & VALGUS (COMBINED MCL AND ACL INJURY)
4. VARUS FORCE (LCL AND ACL INJURY)
5. HYPEREXTENSION FORCE (ACL AND PCL INJURY)

ACL Injury

Mechanisms & Risk Factors

Mechanisms

- Landing
- Rotation/Pivot
- Contact
- Combination

Risk Factors

- Poor landing technique
- Gender: 6-8 higher risk (Anatomical/Hormonal/Technique differences)
- Quadriceps/Hamstrings imbalance
- Footware/playing surface interface
- Playing surface quality

ACL Injury – Risk Factors Gender

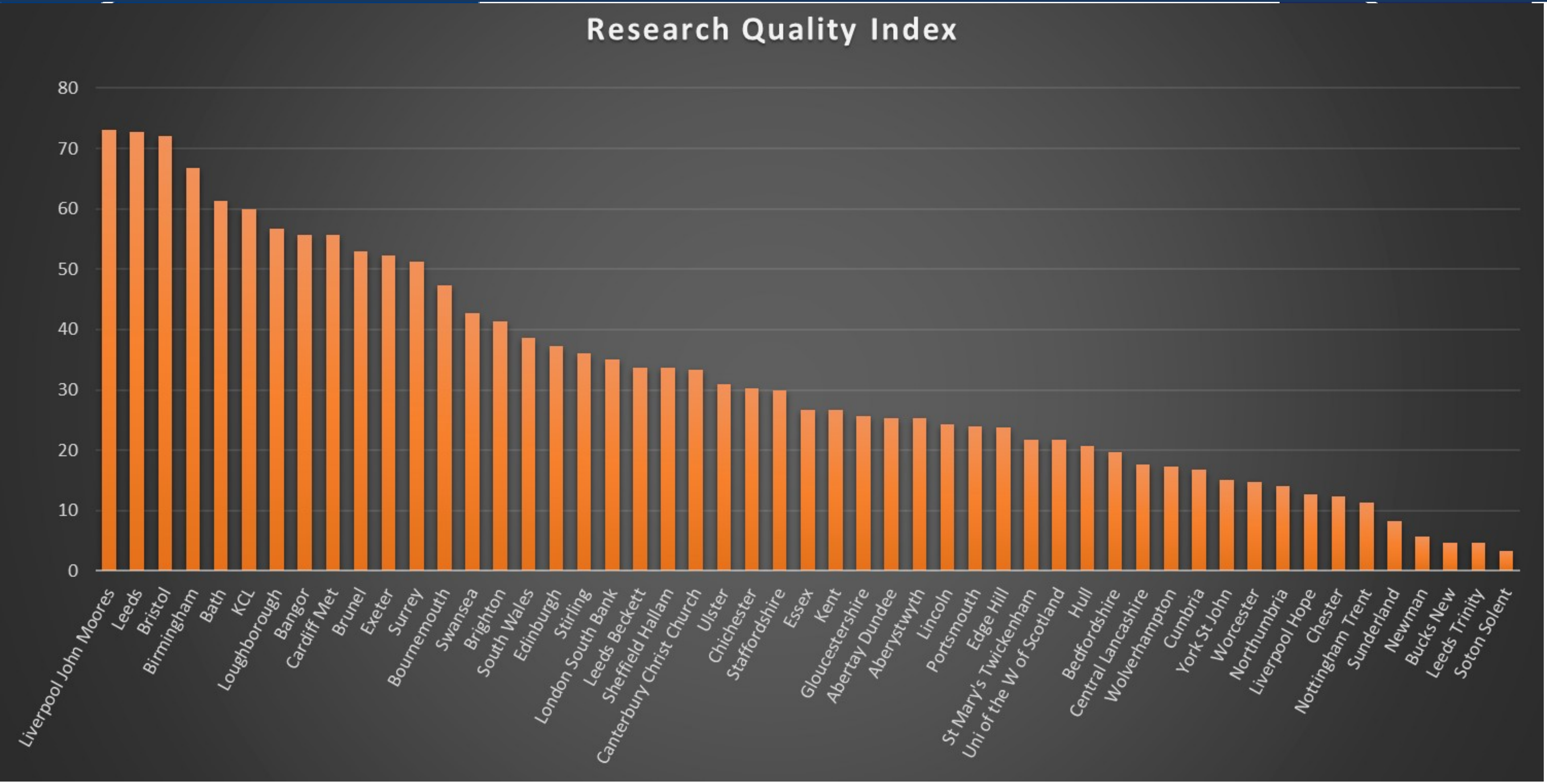
Females:

- 6-8 higher injury rate
- Land with knees less flexed
- Poor hamstrings:quadriceps balance
- Hamstrings protection of ACL reduced
- Hamstring co-activation deficit
- Slow activation of hamstrings

Some questions…

What is a safe range of knee motion during a stopping or landing motion for an athlete in order to prevent ACL injury?

Top ranked institution in the UK for research in sport and exercise sciences (REF, 2014)



Biomechanics of ACL

Calculated load on the ACL

Cycling	**26N**
Single leg squats	**71N**
Lachman test	**89N**
Level walking	**178N**
15 degree isometric contracture	**290N**
Leg extension w/o weight	**490N**
Jogging	**556N**
TKE with 7lb. weight	**622N**

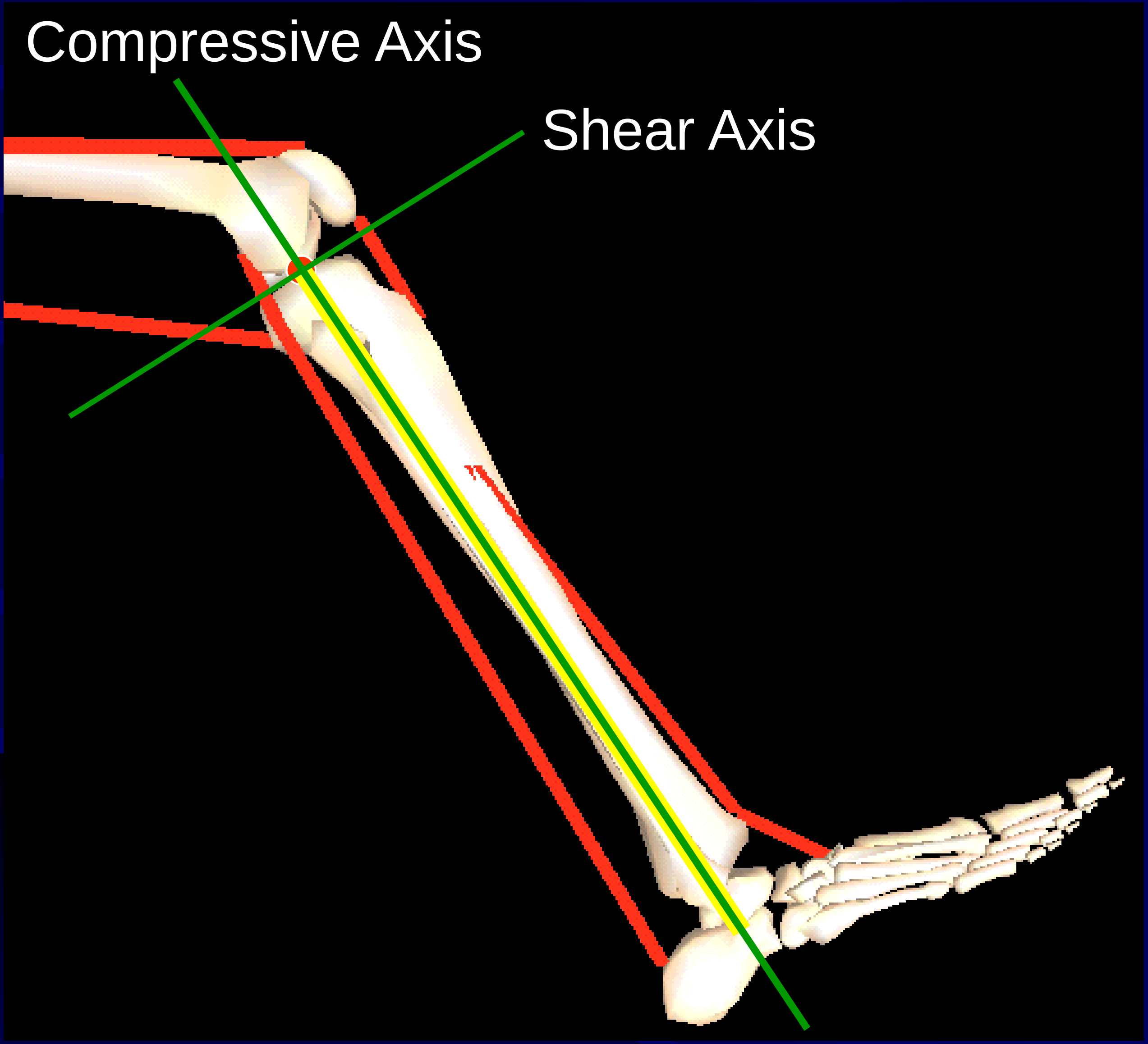
Strains in the anteromedial bundle of the ACL during common activities

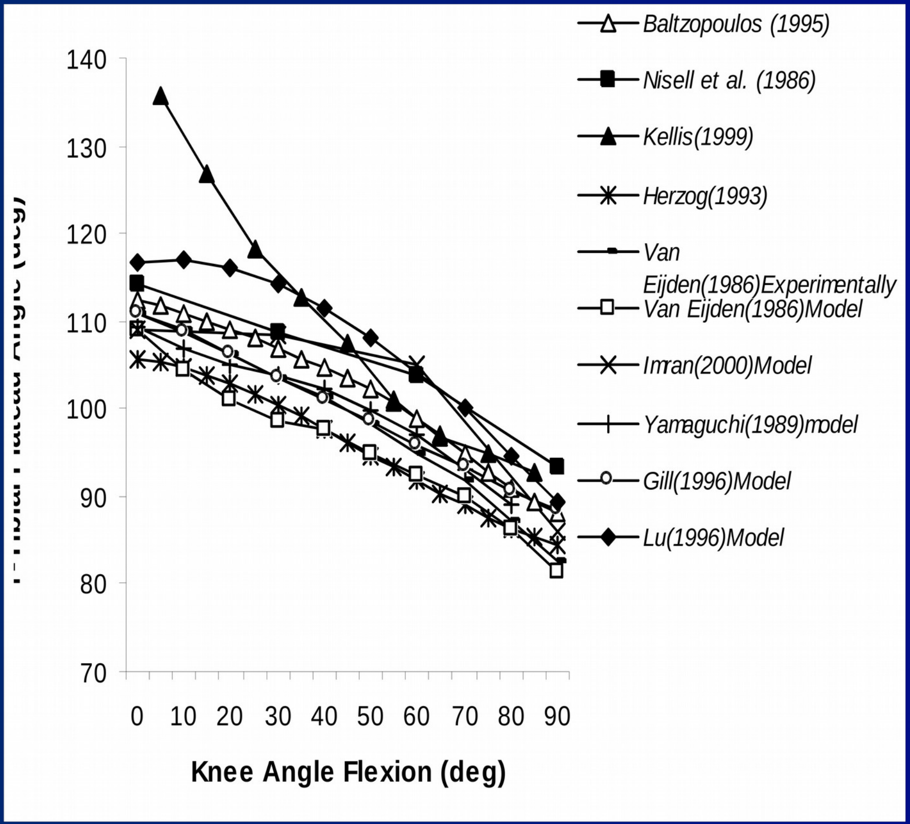
Isometric quads at 15° (to 30Nm of extension torque)	4.4%
Weight bearing - peak strain	3.9%
Active ROM with a 45N weight boot	3.8%
Simultaneous quads and hams contraction at 15°	2.8%
Isometric quads at 30° (to 30Nm of extension torque)	2.7%
Stair climbing (wide variation)	2.7%
Simulated weight bearing (supine)	2.5%
Anterior drawer (150N)	1.8%
Cycling	1.7%
Isometric hams at 15°	0.6%
Simultaneous quads and hams at 30°	0.4%
Isometric quads 60-90° (to 30Nm of extension torque)	0%
Simultaneous quads and hams at 60-90°	0%
Isometric hams at 30-90° (10Nm of flexion torque)	0%
External rotation torque (6Nm at 30° flexion)	0%
Passive range of motion	0%

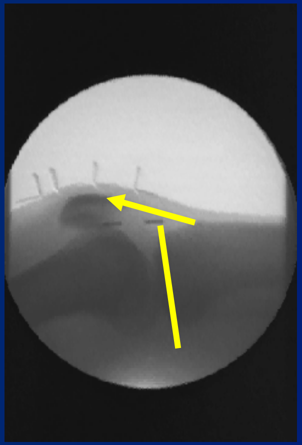
ACL Injury – Risk Factors
Poor Landing Technique

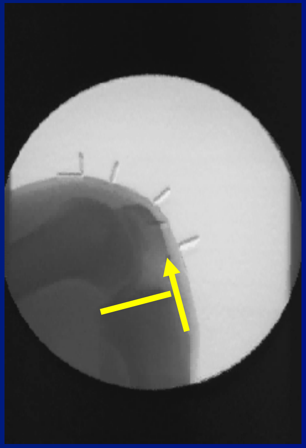
- Reduced Hip & Knee Flexion Angles
- Increased Knee Valgus
- Internal Rotation of the Femur on Tibia

Axes of the Segment & Free Body Diagram

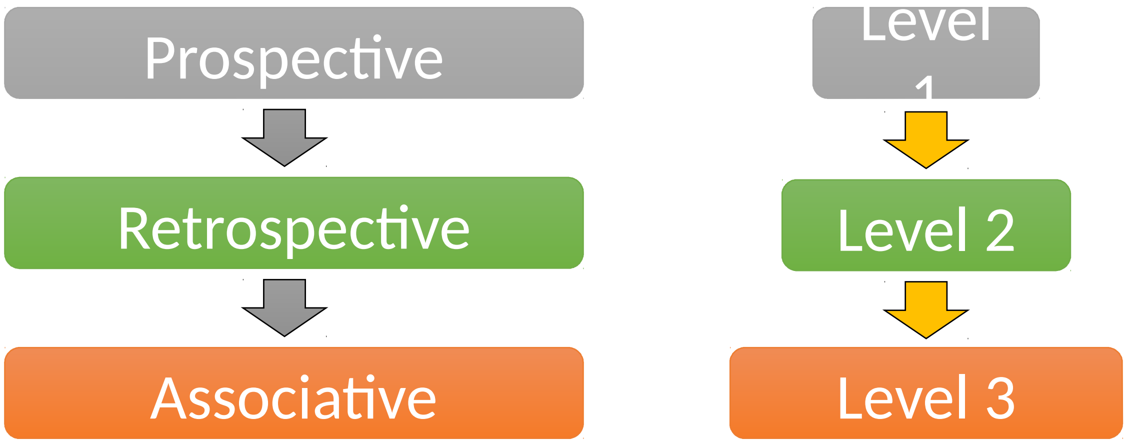



Baltzopoulos (1995)
Nisell et al. (1986)
Kellis(1999)
Herzog(1993)
Van Eijden(1986)Experimentally
Van Eijden(1986)Model
Imran(2000)Model
Yamaguchi(1989)model
Gill(1996)Model
Lu(1996)Model
140
130
120
110
100
90
80
70
0
10
20
30
40
50
60
70
80
90
Knee Angle Flexion (deg)

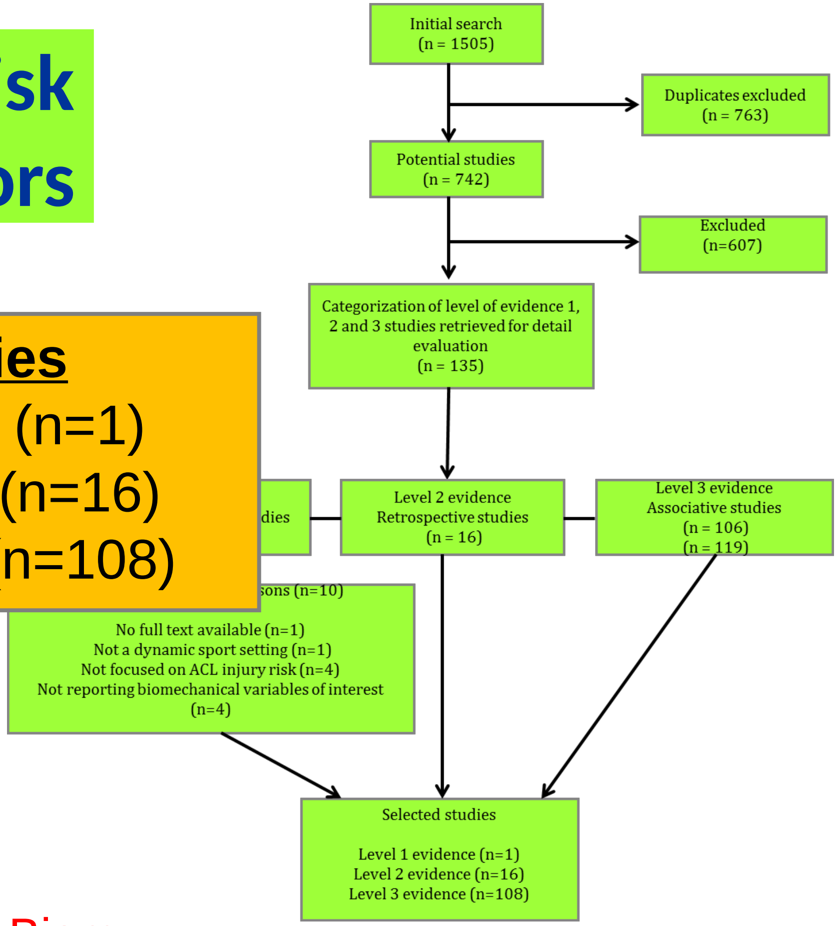




Evidence quality



Systematic Review of Risk Factors



Eligible studies

Level 1 evidence (n=1)

Level 2 evidence (n=16)

Level 3 evidence (n=108)

Sharir *et al*., 2016. Clin Biom