Eccentrics: The Mechanical-Biologic Connection
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Orthopaedics is the study of the effect of mechanical force on biologic tissue

Wolff’s Law: Musculoskeletal Tissue Adapts to the Level Of Externally Applied Force

History of Medical Resistance Therapy
• Julius Wolff 1896 Wolff’s Law: Established Principle of Mechanotransduction
• Tom DeLorme MD 1950’s Progressive Resistance Exercise
• Isokinetics for Knee Rehab 1970’s to Present
• Lumbar Training Devices 1990’s to Present
Principles of Medical Resistance Therapy

1) Specific Diagnostic Conditions
2) Force Application to Specific Anatomic Sites
3) Quantifiable, Accurate, Incremental Resistance Sources
4) Objective Measurements of Pre- and Post-treatment Status
5) Goals of Treatment
Fig. 6. A. Load-resisting combined hip and knee extensor exercise. First phase.
In the late 1980's Arthur Jones Popularizes the concept of Variable Resistance and with it the use of the Isometric Strength Curve.
The Skeleton Receives Mechanical Stimulus from Muscular Force

Positive, Negative and Isometric Measures of Strength were Placed into Hierarchical Structure

Medical - Mechanical Disconnect

Orthopaedics Provides Surgical Solutions
- Mechanical Replacement
- Material Support (Vertebroplasty)
- Bone and Joint Transplant

Medicine Provides Pharmacologic Solutions
- Osteoporosis - Bisphosphonates, BMP's
- Sarcopenia - Hormonal Replacement, HGH
- Arthropreservative Medications

Mechanical Force not used for Medical Therapy
Present Day Programs for Systemic, Non-Specific Skeletal Muscle Anabolism

Exercise-Related Anabolic Stimulation
• High Load-Low Volume
• Low Load-High Volume
• High Intensity
• Interval Training
• Neural Adaptation

Non-Exercise Methods for Muscle Anabolism
• Nutritional Supplementation
• Androgenic Hormones
• Hypoxia
• Nitric Oxide
• Acupuncture
• Vibration

Restricted Blood Flow Stimulus
• Flow Restriction with Low Intensity Resistance
• Increased Serum HGH
• Increased Circulating IGF-1

“Myo-Fiber is bigger than Your-o-Fiber”

Concentric Muscle Force Affects Musculoskeletal Homeostasis
• Mediated through Musculoskeletal Continuum
• Affects Anabolic:Catabolic Balance
• Known Mechanical Sensitivity of Tissues
• Explains Local Response of Isolated Muscles
• Increased Serum Levels of HGH and Testosterone in response to intense large muscle group exercise

Structural “Overloading” Invokes a Reparative Response
• Explosive Ribosomal Upregulation
• Elaboration of Mechano-Growth Factors
• Myogene Expression
• Stem Cell Activation
• Repair and Regeneration

What is Overload?

Loading: Muscle Confers Energy to the Weight Being Lifted

Overload: External Loading Creates Strain Energy in Muscle
The Duality of Muscle

**Force Generation**
- Concentric
- Contractile Proteins
- Actin
- Myosin
- Sliding Filament Theory
- Shortening
- Requires ATP for energy
- Metabolic Stress

**Force Transmission**
- Eccentric
- Non-Contractile Proteins
- Titin
- Alpha-Actinin
- Winding Filament Theory
- Lengthening
- Elastic Force Absorption
- Structural Micro-Injury

Eccentric Force is an Ideal Therapeutic Agent

**Theoretical Benefits**
- External "Overload" Mechanically Signals Musculoskeletal Tissue
- Targets the Entire Musculoskeletal Continuum
- Requires Little Energy Expenditure
- "Threshold Concept" of Maximal Stimulation

**Appropriate "Dosing"**
- Site of Action (Where?)
- Magnitude (How Much?)
- Duration (How Long?)
- Frequency (How Often?)
- Chronicity (How Many?)
- Resistance (What Type?)

The “Threshold Concept”:

**Thermodynamics**
Thermodynamic Threshold under Isokinetic Conditions

Force goes up

Rate of Heat Production Goes Down

Is It Safe?

Physics

Physics of Muscular Effort

Force = Mass x Acceleration
(No Movement=No Energy Transference= No Work)
Physics of Muscular Effort

Work = Force \times Distance

Physics of Muscular Effort

Power = \frac{Force \times Distance}{Time}

Physics of Muscular Effort

Power = \frac{Force \times Distance}{Time}

Power = Force \times Velocity
Force and Velocity Determine Power

The Maximum or Most Efficient Point of Transferring Energy from the Muscle to the load being moved

What are the Physiologic Correlates of Power?

A. FORCE

Physiologic Equivalent of Force

The Contractile Myofilament is the Smallest Unit of Force Production in Muscle and Consists of Serial Sarcomeres.
Physiologic Equivalent of Force
By sliding towards one another the sarcomeres create opposing forces that cancel each other out, no matter how many sarcomeres are in series.

Physiologic Equivalent of Force
No matter how long a myofilament is, it only generates the force of one sarcomere, i.e., the unopposed sliding filaments at each end of the myofilament.

Any cross section of a muscle is a representation of the maximal force that can be created by the number of myofilaments in that section.

Physiologic Equivalent of Force

ONLY INCREASING CROSS SECTION WILL INCREASE FORCE
What are the Physiologic Correlates of Power?

**B. Velocity**

Physiologic Equivalent of Velocity

Muscles Don’t Contract...They “twitch”.

The “All or None” theory states that when stimulated, every sarcomere in the stimulated myofibril contracts simultaneously IRRESPECTIVE OF THE LENGTH OF THE MUSCLE.

Physiologic Equivalent of Velocity

All the Sarcomeres close SIMULTANEOUSLY in the same fraction of a second, No Matter How Many Sarcomeres are in Series.
A Very Long Fibril Will Contract in the Fraction of a Second as a Short Fibril

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Physiologic Equivalent of Velocity

Therefore:

A 100cm muscle will fully contract in .01 sec with a Velocity=1cm/sec

A 10cm muscle will fully contract in .01 sec with a Velocity= 0.1cm/sec

**Long Muscles are Always Faster**

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Physiologic Equivalent of Power

Power = Force x Velocity

Force~Cross Sectional Area

Velocity~Muscle Length

Power ~ Cross Section x Length

THE LARGER THE CROSS SECTION
THE GREATER THE POWER
Physics of Eccentric Resistance

- The absolute value of the Force-Velocity product is high
- The Direction of Travel is OPPOSITE of the Concentric Velocity, i.e. Negative
- Therefore the Power is LOWEST when the weight is travelling the fastest
- The SLOWEST speed of eccentric travel, therefore has the highest Power efficiency

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Is It Safe?

Physiology

*The Winding Filament Theory*
Figure 1. (a) Schematic of a skeletal muscle half-sarcomere illustrating the layout of titin (yellow with a red N2A segment). Each titin molecule is bound to the thin filaments (blue) in the I-band, and to the thick filaments (green) in the A-band. Note that, for simplicity, thick filaments are illustrated as double-stranded, whereas in vertebrate skeletal muscle, they are actually triple-stranded. The N2A segment is located between the proximal tandem Ig segment and the PEVK segment.

Figure 1. (b,c) Ca$^{2+}$-dependent binding of N2A to thin filaments. (b) Resting sarcomere at slack length at low Ca$^{2+}$ concentration (pCa = 9). (c) Upon Ca$^{2+}$ influx (pCa = 4.5), N2A titin binds to the thin filament (blue), which shortens and stiffens the titin spring in active sarcomeres. (Nishikawa KC, et al. Proc R Soc B 2012; 279(1730):981-990 with permission.)

Figure 2. Schematic illustrating the winding filament hypothesis. (a,b) Ca$^{2+}$-dependent binding of N2A to thin filaments contributes to length-tension relationship. If N2A (red) binds non-selectively to thin filaments (blue) in the presence of Ca$^{2+}$, and if the binding site depends on sarcomere length at the time of Ca$^{2+}$ influx, then a plateau is predicted in active force at sarcomere lengths between (a) 2.4 and (b) 2.6 µm in rabbit psoas muscle.
Figure 2. (c,d) Cross-bridge cycling results in titin winding. (c) Cycling of the cross-bridges winds PEVK on the thin filaments (arrow indicates direction of rotation). In the model, the winding angle depends only on sarcomere geometry. (d) Stretch of an active sarcomere extends the PEVK segment and enhances the active force. (From Nishikawa KC, et al. Proc R Soc B 2012; 279(1730):981-990 with permission.)

The Transference of Loading to a Non-Contractile Molecule Changes the Role of the Muscle from a Dynamic Lengthening Function to a Static Length Maintenance Function

The Position of Titin in the Sarcomere in the Lengthened State
Detail of Myosin Helix Around Titin

Winding Filament Mechanism for Maintaining Tension During Filament Shortening
Titin Transmits and Signals the Eccentric Force

The “Threshold Concept”:

What Happens When the Overload Signal Reaches the Cell?
Direct Physiologic Effects of Forced Muscle Lengthening

Exceeding the Threshold Results In:

- Ribosomal Activation
- Myogenic Activation
- Myofibrillar Branching
- Stem Cell Differentiation
- Local Growth Factors
- Systemic Growth Factors

Local release of paracrine-like hormonal agents


The cellular responses include up-regulation of Myogenes


The “Threshold Concept”:

Repair and Regeneration Consequent to Eccentric Overload
Myofibrillar Disruption and Resultant Branching

Eccentric Exercise Facilitates Mesenchymal Stem Cell Appearance in Skeletal Muscle (Valero, 2012)

Part II: Pathology

Myotendinopathies
The long-term effect of eccentric activity on a muscle-joint unit is to increase the structural integrity of the involved tissues.


Tendinopathy is used to describe impaired tendon healing characterized by pain, swelling, and impaired performance.

- Tendinitis
- Tendinosis
- Myotendinosis

With an aging population the number of patients with tendinopathies is in the hundreds of thousands and is increasing.

Achilles tendinitis


Patellar Tendinopathy


Rotator Cuff Tendinitis

Hamstring Muscle Strains


Eccentric exercise of the involved tendon has the strongest clinical evidence for effectiveness of treatment


Part III: Safe and Effective Treatment

What Type of Resistance?

How Much Resistance?

What Speed of Movement?

What Frequency of Workouts?
Essential Characteristics of Eccentric Force Application

1) Quantifiable, Consistent Level
2) Incremental
3) Safe Maximal Limit
4) Speed and Direction Response
5) Controlled Concentric/Eccentric Transition
6) Non-elastic Properties

Stable-Responsive
- Free Weights
- Weight Stacks
- Cam-Modified
- Leveraged Weights

Stable-Non-Responsive
- Hydraulic
- Isokinetic

Unstable-Responsive
- Pneumatic
- Electromagnetic
- Elastic (ENERGY ACCUMULATION)

Energy Transferred
Muscle Accumulates Energy
Resistance Source Accumulates Energy

Isotonic/Isoinertial Eccentric Resistance
- When resisted does not transfer higher levels of tension into muscle, simply slows down
- Speed correlates to exercise intensity
- Allows the principles of “Progressive Resistance” to be employed Eccentrically
- Can be mechanically modulated (i.e. cams) to be proportionate throughout the range of motion
Part III: Safe and Effective Treatment

What Type of Resistance?

How Much Resistance? (CON)

What Speed of Movement?

What Frequency of Workouts?

Essential Characteristics of Concentric Force Application

none

Part III: Safe and Effective Treatment

What Type of Resistance?

How Much Resistance?

What Speed of Movement? (CON)

What Frequency of Workouts?
What is the Ideal Concentric Resistance and Speed of Movement?

Ideal Concentric Resistance

- Approximates the Peak Power output at each repetition during a single set
- Value changes as fatigue reduces muscular contractility
- Therefore, ideal concentric resistance would decrease during each individual set
- Isokinetic Resistance inherently allows this
- It is a Range of Values; Not a Single Number

Part IV: Safe and Effective Treatment

What Type of Resistance?

How Much Resistance? (ECC)

What Speed of Movement?

What Frequency of Workouts?
Safe and Effective Resistance

Progressive Eccentric Resistance

• Set Parameters for Successful Completion of Repetition and Set Number
• Increase Eccentric Resistance by 5-10% if target goals made
• Repeat

Part IV: Safe and Effective Treatment

What Type of Resistance?

How Much Resistance?

What Speed of Movement? (ECC)

What Frequency of Workouts?
Target Tissue

Muscle
- Length Increases
- Different Areas of the Muscle Affected at Different Lengths
- Metabolic Energy Reserves Influence Force Production

Tendon
- Length Constant
- Tendon Loading Indifferent to Muscle Length
- No Metabolic Limitations

What is the Ideal Eccentric Movement Speed?

Muscle
- Maximum Stimulus from Static Load (No Movement)
- Non-Trained Areas of Muscle
- Ligaments Exposed to High Force Levels
  - Spinal Flexion Harmful
  - Wrist Flexion Harmful
  - Knee Hyperextension

Tendon
- Indifferent to Muscle Length or Joint Position

What is the Ideal Eccentric Movement Speed?

Muscle
- Slow Speed 4 to 6 second descent
- Static Load at Desired Joint Position
  - Lumbar Lordosis
  - Wrist Extension
- Slow Lengthening and Static Hold at Point of Maximal Muscle Tension

Tendon
- Indifferent to Muscle Length or Joint Position
What is the Safest Workout Frequency


The Traditional Determination of the Number of Repetitions is the Onset of Concentric Failure

- Classic Concentric Failure

- Advanced Failure Alternatives

- Combined Concentric-Eccentric Failure Models

Conventional Six Rep Set
True Concentric Failure

Eccentric Overload Set for Hypertrophy

Eccentrics Require Little or NO energy Substrates to Continue to Resist Lengthening

Eccentric Failure is Simultaneous with Concentric Failure
Maximal Eccentric Load and Concentric Work

Minimum Limb Function Before Beginning Resistance Therapy
- Maximum Range of Motion Achieved through Active Contraction and/or Passive Assistance
- Pain does not prevent Active or Passive Ranging of Joint
- Patient Tolerates normal daily activities involving affected muscle group
- Clearance by Physician to begin Resistance Based Therapy

A Selected Weight at the Mid-Range-of-Motion
**The Static Load Test of the Shortened Muscle: Isolated Single Limb**

- Therapist Sets Resistance to by Raising Desired weight and “pinning” it at testing position
- Place Patient in Machine
- Patient raises weight with and holds it for three seconds
- Repeat till patient cannot raise or hold weight for three full seconds

**Theory of Assistive Loading**

- Early therapy is limited by pain inhibition of the affected joint
- Pain inhibition is mediated by stretching the Golgi Tendon Organ (GTO)
- The GTO inhibits contracting the lengthened muscle
- By applying the load to the shortened muscle, GTO inhibition of contraction is reduced

**Begin Unilateral Training: Manual Assistance**

- Establish Full Range of Motion in Machine
- Set Lowering Weight at Static Test Load
- Provide Assistance of approximately 75% of Maximum Static Load (25% Concentric Resistance)
- When patient can lower the eccentric load for 10 consecutive repetitions; Reduce the Concentric Assistance to 50% (i.e. Increase the amount of weight being lifted)
Graded Resistance Bands to Provide Assistance During Concentric Phase

Heavier Gauge Resistance Bands to Provide Appropriate Resistance

End of Unilateral Training

When the patient completes two consecutive sets of ten repetitions with 50% of assistive help using the injured limb, the patient can advance to bilateral training
Part IV: Begin Bilateral Strengthening

- Structural Strengthening is NOT functional exercise
- The goal is to expose the muscle and tendons to high loads so they may structurally adapt
- Bilateral Loading provides a stable shoulder girdle or pelvis through balanced muscular force
- Bilateral loading exposes the injured extremity to higher loads than unilateral loading

Training Set

- Set the Weight Stack at the highest weight lifted after three trials (1RM)

Begin Bilateral Training: Graded Assistance

- Establish Full Range of Motion in Machine
- Set Lowering Weight at 1RM
- Supply Concentric Assistance of about 50% for a target of ten repetitions
Treatment Plateau: Phase II

- Begins with inability to complete 10 repetitions with reduced assistance
- Then reduce the lowering weight 5-10% and maintain same assistance grade
- This effective lowers both the concentric and eccentric resistance
- If patient is successful, repeat decreasing the amount of assistance

Examples of Eccentric Capable Units

Future Directions

- Recognition that Eccentric Loading is a Valid Medical Intervention
- Reduces Physical Frailty
- Treats Osteoporosis and Sarcopenia
- Can be given in “Minimum Effective Doses”
- The hormonal effect of myokines can fight diabetes, heart disease, and vascular disease
The End