The Back Story: A New Strategy for the Aging Lumbar Spine

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KEY POINTS

- **Upright posture, lifting, and carrying require the lumbar extensor muscles.**
- **The strength for lifting comes from extending the pelvis and the knees.**
- **Lumbar muscular tension creates the stability to transfer the force of lifting.**
- **Specifically, the eccentric action of the lumbar extensors maintains lumbar stability.**
- **Loss of muscle mass and disc height can lead to weakness, kyphosis, and back pain.**
- **Preventative strengthening forestalls muscle loss and promotes lumbar stability.**
- **Enhanced eccentric training is necessary to restore eccentric strength.**
- **Eccentric training requires less sets, lower exertion, and fewer training sessions**
- **Train the essential movements of lumbar, hip, and knee extension**
- **Begin eccentric resistance submaximally and progress to a supramaximal level**

Forward

Although widely recognized as an important means of preserving health and function in the elderly, resistance training has been mainly seen through the lens of physical aesthetics, fitness influencers, competitive weightlifters and body builders. Physical therapists focus largely on regaining function for daily activities. For the elderly, who would benefit most from optimizing their strength, there is not a clear medical strategy of resistance training. Part of conveying the medical importance of resistance training is to not only focus on the essential muscles for mobility but also deliver the most efficient stimulus. Thus, there are two areas of emphasis in this treatise. The first is establishing the “minimum effective resistance dose” that patients require to increase their strength. The second is “Which are the crucial exercises needed to ensure independence in aging”?

From standing, to walking, to lifting, to sports, and finally to aging independently the spine and, specifically, the lumbar spine is critical. However, the low back and its care remains complex, complicated, and confusing. There have been hundreds of treatments used going back hundreds of years proffered to treat low back conditions. Even the “modern” approaches from 50 years ago came from conflicting theories that still today remain unresolved. Through a series of events in my training at the University of Florida, I became involved in two areas that I have been working on for the last 40 years, eccentrics and the lumbar spine. Although I came to each of these topics separately, I began to realize that they were inextricably linked. What came out this realization is a better understanding of spinal function and a potential pathway for management of spinal disorders.

As I analyzed the relationship of eccentrics to spinal function, there were some relationships that required reasoned interpretation because none of the models had taken into account the eccentric function of muscle. The main thesis is that under heavy loads the lumbar muscles must function eccentrically to prevent injury to the lumbar spine. This furthermore leads to an explanation of how eccentrics behave according to Hook's Law for their movement and strength. A minor missing puzzle piece was to suggest how the actin-myosin filaments behave during eccentric lengthening. In addition, Richard Lieber's work was important to show how the continuity between the muscle's intracellular cytoskeleton to the extracellular matrix enabled the spine to transmit heavy loads. Finally, in terms of practical applications, the Australians should be credited for distinguishing between "Pushing Isometrics" and "Yielding Isometrics". This monograph takes these isometric distinctions a step further by including supramaximal yielding isometrics.

It is my hope that these conjectures help complete the understanding of muscles during conditions of overload. Ultimately, I hope this proposal can improve low back care and help our aging population to maintain a stable, functional low back into their advancing years. Although this treatise focuses on the lumbar spine, eccentrics are involved with many other movements as well. I hope that the principles discussed here may eventually be applied to other areas of human function.

Introduction

The spine is a relic of evolution. For 100 million years, it functioned in our vertebrate predecessors as a horizontal structure that formed a framework for various species to contain their nervous, vascular, and digestive systems. For locomotion, muscles would undulate from side-to-side to create forward progress. Movement was first aided in the oceans by fin appendages and later by the formation of a tail. In the slow progression onto the land, the appendages developed bones and joints that could support and lift the spine off of the earth and walking. The quadrupeds became excellent walkers and runners. The horizontal spine was particularly suited to connecting the hind limbs to the fore limbs. In reptiles, the limbs exerted asymmetric torque on the body, bending the spine laterally to advance the hind and fore limbs. When explosive force was required, both hind limbs would coordinate to propel the lower body and the spine would flex and then extend, to launch the upper torso forward. The spine was an efficient and effective mechanism for the locomotion for terrestrial quadrupeds.

It wasn't till about 4 million years ago that the spine was slowly adapted to the upright, bipedal posture. A breed of apes left the safety of the African jungle and strayed out to the plains of the African savannah. The skeletal remains they left had many anatomical features suggesting upright locomotion. In 1978, a set of 3.6 million-year-old footprints discovered by Paul Abell at

Laetoli gave proof of bipedal locomotion (Raichlen D, 2008). For our primate ancestors to extend the trunk off the ground, two major adaptations to the pelvis and low back had to occur. The first is that pelvis had to rotate from a horizontal position to a vertical position (Snell, 1968). All of the muscles that attach from the pelvis to the lower extremities had to change their direction of pull from horizontal to vertical to balance the upper body on the hip joints. The most notable of these were the gluteus maximus muscles. Whereas in quadrupeds the gluteal muscles only extended the thighs so as to push body forward; in the upright position the gluteal muscles adapted to rotate the pelvis into the extended position, thus placing the trunk, head, and arms in the upright posture. The vertical pelvis and spine became a key event in the evolution of man.
In the transition to the upright posture the need to extend the spine became the dominant function. Thus, the individual muscle groups; the iliocostalis, longissimus, sacrospinalis, and multifidi, while retaining some of their independent function, became consolidated to extend the spine upward as the "spinal erectors".

The paradox of the spine is that it must retain the mobility necessary to crouch, sit, climb, and bend, while still providing the rigidity and stability of doing heavy upright labor. It is the purpose of this treatise to show that there is a dual function of muscle that can provide movement for mobility needs, yet also can resist large external forces to promote upright posture.
The complexity of the low back has led to widespread confusion and speculation about how the spine functions, what causes problems, and which treatments are best. To improve the understanding of this structure it is important to review how we came to understand the role of muscular forces in spinal stability.

The Roots of Spinal Biomechanics: Nachemson versus Farfan

The Lumbar Extensor Proponents

Modern understanding of spinal biomechanics can be attributed to the early work of Hirsch and Nachemson (Hirsch & Nachemson, 1954). These studies focused on the lumbar intervertebral discs and in particular the compressive forces to which they are exposed. Nachemson further shed light on the effect of posture on the compressive force on the disc with his classic article with human subjects (Nachemson, 1964) (Nachemson & Elfstrom, Intravital dynamic pressure measurements in lumbar discs: a study of commom movements,maneuvers and exercises, 1970 1). Nachemson inserted manometric needles into the lower lumbar discs of living subjects. As the subjects assumed postures that flexed the trunk forward and placed the entire axial load of the spine directly on the disc, the pressures rose dramatically. The intradiscal pressure measurements of stoop lifting (flexing forward) were more than twice that of squat lifting (Nachemson, 1964). More importantly, when loads were carried in the upper extremities during flexion, the compressive loads approached the limits of the structural strength of the lumbar disc.

The strengths and weaknesses of the lumbar spine were suggested by these early studies. The lumbar disc was found to be able to tolerate heavy loads when the spine was in extension, but could be compromised when lumbar flexion occurred. This was interpreted to represent the load sharing capability of the posterior facet complex in extension. Early biomechanical studies began to reveal the complex interactions of the facet joints and ligaments and the intervertebral disc (Schultz, Belytschko, & Andriacchi, 1973). These investigations showed the protective role of facet load sharing provided for the intervertebral disc. The emerging view was that flexion exposed the disc to injury, but extension allowed the lumbar spine to tolerate heavy axial loading.

Proponents of the Torsion-Based Lumbar Spine

On the other side of the world, in Australia, the view that the injury mechanism was flexion was being challenged. In 1970 Farfan published his theory that torsion caused injury to the lumbar spine. He studied the structure of intervertebral disc and surmised that the collagen pattern was expressly designed to prevent failure from twisting. In a post-mortem study he reported the predominant pathology in the outer annulus of disc were torsion injuries (Farfan, Cossette, Robertson, Well, & Kraus, 1970). His interpretation of these findings was that the disc was most susceptible to injury during twisting. He went on to support this view with a biomechanical study of the L3-4 disc suggesting that muscles that create torsion were the primary movers of the lumbar spine (Cossette, Farfan, Robertson, & Wells, 1971). Thus, the "Extension versus Torsion" debate was founded.

The extension faction, under Nachemson, could easily point to lumbar extensor muscles as the means of preventing flexion and protecting lumbar discs under heavy loads. However, the torsion proponents did not have a clear muscular system that could generate enough force to create the lifting forces seen in biomechanical studies. To address this deficiency, Farfan began to work with Gracovetsky, a nuclear physicist with mathematical modeling skills. This collaboration resulted in an elaborate theory of human locomotion about the importance of the lumbodorsal fascia and the abdominal muscles in human motion (Gracovetsky S, 1977). Gracovetsky and Farfan promoted the influence of rotational muscle forces on the lumbar spine, but were challenged to demonstrate how rotational forces could be resolved in order to create an extension moment that could assist in lifting. They theorized that it is the effect of the abdominal muscles on the lumbodorsal fascia to promote extension (Gracovetsky S, Farfan H F, 1981). Moreover, they emphasized the role of the abdominal muscles in creating intra-abdominal pressure (IAP) in order to assist in the extension of the trunk during lifting. They called this the "unified theory" of the lumbar mechanism and used this mechanism to explain both the function and the pathology of the lumbar spine.

Despite the evidence for the importance of lumbar extensor muscles, Farfan's Australian group was continuing to promote the abdominal muscle's role. His theories and his collaboration with Farfan, helped further disseminate the proposition that the abdominal mechanism was a major effector of spinal stability (Gracovetsky S F. H., The mechanism of the lumbar spine, 1981). The abdominal musculature's capability to assist spinal stability was proposed to occur through a direct effect on the lumbodorsal fascia; an indirect effect through IAP. These theories were put to the test in the early lifting biomechanical studies being performed at that time.

IAP as an Indirect Lifting Force

The early researchers of lumbar lifting mechanics were struck by the paradox that when performing a heavy lift not only were the calculated lifting forces too high for the spinal erector muscles to generate, but also the calculated compressive forces were in a range that could damage the intervertebral disc (Bartelink, 1957). The abdominal muscles were thought to decrease the demands of spinal extension on the spinae erectors through increased IAP. Early researchers simply measured IAP while subjects performed various lifting tasks (Nordin, Elfström, & Dahlquist, Intra-abdominal pressure measurements using a wireless radio pressure pill and two wire connected pressure transducers: a comparison., 1984). Early studies demonstrate the contribution of IAP to lifting (Farfan H. F., 1973) (Cholewicki, Juluru, & McGill, 1999a) (CRESSWELL, GRUNDSTRÖM, & THORSTENSSON, 1992). Hodges was able to demonstrate significantly increased stiffness of the lumbar spine occurring through increased IAP; however, it did require tetanic stimulation of the phrenic nerve (Hodges, Eriksson, Shirley , & Gandevia, 2005). Intra-abdominal pressure appears to be position dependent. When the spine is in the flexed position there are increasing levels of IAP (MARRAS , Joynt, & King , 1985) and when asymmetric movements are being performed (Marras & Mirka, 1996). The interpretation was that IAP tends to engage to assist with heavier lifts and awkward lifting positions.

Conversely, other studies showed that the increase in intra-abdominal pressure did not occur in all lifting activities at all times (Mairiaux , Malchaire , Vandiepenbeeck , & Bellela, 1988). In addition, the assistive force created by IAP only occurred suddenly and based on the timing and force created was merely a "by-product of the co-contraction of the trunk muscles". (Marras & Mirka, 1996). The lack of significant effect of the abdominal mechanism on lifting was likewise demonstrated by Schultz. His study predicted forces on the lumbar spine by using models of extensor muscle force alone and then validated the results by directly measuring the intra-discal pressure. Using this method, he found that by just including five pairs of lumbar extensors, he was able to accurately predict the resultant intra-discal pressure. (Schultz, Andersson, Ortengren , Haderspeck, & Nachemson, 1982). His in vivo results did not require any additional forces and therefore the need for IAP was diminished as a necessary component for spinal stability.

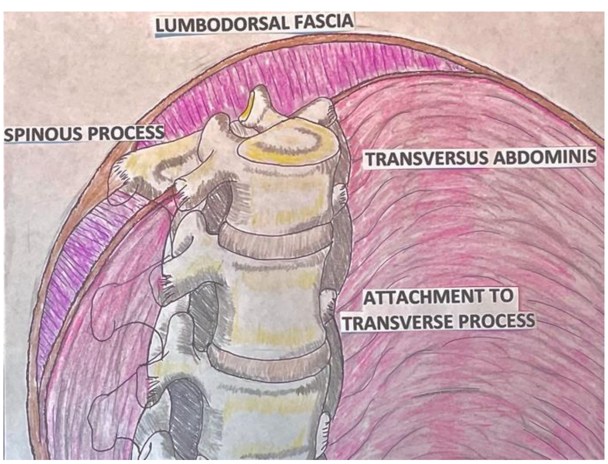
Other studies also questioned the ability of the abdominal mechanism to assist lifting because the flexion moment created by the abdominal muscles themselves can cancel the extension moment created by the IAP. In one study the absolute force of IAP in fact created an extension force but the effect was cancelled by the flexor moments created by the abdominal muscles (Arjmond & Shirazi-Adi, 2006). In an elaborate finite element analysis of the magnitude of trunk muscle forces necessary to stand in extension, neutral, and 30 degrees of flexion, the extensor muscles were called upon to create hundreds of Newton-meters of force but "Intra-abdominal pressure does not have a very strong influence on spinal load and muscle forces for the loading cases studied." (Rohlmann, Bauer, Zander, Bergmann, & Wilke, 2006). There was one study that employed the most elaborate modeling software to address this issue. It appears that the pneumatic effect of the pressure in fact exceeds the muscular flexion moment. This group has calculated a 19% to 31% theoretical increase in extension force (Stokes, Gardner-Morse, & Henry, 2010). These findings have not been corroborated with physical testing.

It was also noted that lifting belts have been used in the workplace and in strength sports with the theory that they increase IAP. Multiple studies of lifting belts have not resulted in a clear consensus of their efficacy for injury prevention. (Thomas JS, Effect of lifting belts on trunk muscle activation during a suddenly applied load. Human Factors, 1999). In strength sports the use of belts do contribute to increased IAP, but inconsistently (Harman, E A "Effects of a belt on intra-abdominal pressure during weight lifting." Medicine and science in sports and exercise,1989) (McGill, S "The effect of an abdominal belt on trunk muscle activity and intra-abdominal pressure during squat lifts." Ergonomics 1990). Another mechanism for belt efficacy is thought to be increased intra-muscular pressure of the lumbar muscles (Miyamoto K, Effects of abdominal belts on intra-abdominal pressure, intra-muscular pressure in the erector spinae muscles and myoelectrical activities of trunk muscles Clin Biomech 1999 Feb). Thus, intra-abdominal pressure may contribute to the lifting capability of competitive strength athletes, but mainly through the use of external abdominal support. Intra-abdominal pressure appears to be an adjunctive mechanism, but is not a primary source of spinal extension.

Abdominal Muscles and Direct Lifting Force

Aside from the role of intra-abdominal pressure, there was a theory that the abdominal muscles themselves create the needed lifting force. In 1985 Farfan and Gracovetsky revised their human locomotion theory into a "unified theory of spinal function" (Gracovetsky S F. H., 1985). Aside from IAP, the ability of the abdominal muscles to create an extensor moment was theorized to occur through either direct force transmission or through increased intra-compartmental pressure generated by lumbodorsal tension. Because the tranversus abdominis muscle inserted on the lumbodorsal fascia posteriorly and on the transverse processes of the spine, it was proposed that the tensile force of the tranversus abdominis muscle could create an extension moment.

Although these abdominal muscles insert perpendicular to the extensor moment making their effectiveness highly unlikely, some anatomists identified some oblique fascicles that attached superiorly (MacIntosh & Bogduk, 1987). One study dissected the transversus abdominus and applied force through strain gauges on unembalmed cadaver specimens. They found that with a 10 N force that they could detect intersegmental motions in the lumbar spine (Barker , Briggs, & Bogeski, 2004 29(2)). These findings have only been reported in cadavers, and the ability of the transversus abdominis to create spinal motion in vivo has not been documented. Even Gracovetsky admitted that "Too little of the abdominal musculature attaches to the thoracolumbar fascia to generate a significant tension." (MacIntosh, Bogduk, & Gracovetsky, The biomechanics of the thoracolumbar fascia, 1987). Subsequent biomechanical modeling of the moments created by muscular force during lifting have failed to show that the absolute force created by contraction of the abdominal muscles have any meaningful resultant extensor effect (McGill & Norman, 1988).



More recently biomechanical models have been developed that combined muscle modeling techniques, finite element analysis and EMG activation information (Arjmand, Gagnon, Plamondon, Shirazi-Adl, & Lariviere, 2009). These models have found that in multi-joint lumbar spine movements the effect of the abdominal muscles on spinal unloading is negligible.

Finally, clinical studies were done to see the effect of transversus abdominis muscles in living subjects. One study showed that even when strong contractions of the transversus abdominis were recorded there was little added benefit to spinal stability (Stokes, Gardner-Morse, & Henry, 2011). Efforts to manipulate the effect of intra-abdominal pressure through either strengthening or fatiguing the abdominal muscles failed to show any change in the onset or duration of intra-abdominal pressure during lifting (Legg, 1981).

Thus, the anatomic finding that the abdominal muscles attach to the lumbo-dorsal fascia is not, in and of itself, enough evidence to suggest that the abdominals have a significant role in spinal stability.

Neuro-motor Control Theories

Absent evidence that the abdominals could directly extend the spine, other Australian researchers proposed that it is not the absolute "capacity" of the abdominals that determines their effect, but rather their "control" which creates a significant effect (Hodges & Richardson, 1997). They proposed a neural mechanism by which muscles could respond to an external stimulus with what was described as a "feedforward" effect. In their model the subject would respond to a physical challenge, such as a ball being thrown at them by a pre-emptive transversus contraction. Their assertion was that even before the limbs moved to catch the ball, the event first caused a reflexive contraction of the transversus abdominis. As proof of this, they measured this muscle response to an external stimulus in patients with low back pain. They reported that in the group with low back pain the transversus abdominis muscle contracted 50msecs (1/20th of a second) slower than the abdominal muscles in patients without low back pain. Their conclusion was that the delay in transversus abdominis activation was causative for the presence of low back pain. The inability of this muscle to pre-emptively contract was felt to put the lumbar spine at risk for injury.

This neuro-activation mechanism of the abdominal muscles as a primary spinal support has been challenged (Lederman, 2010). Since the transversus abdominis' contribution to spinal stability is minimal, he notes that the appearance of this contraction delay, in no way can be interpreted as a causative factor for low back pain. In addition, there is no known reflexive pathway to initiate a transversus abdominis contraction before the limbs react. For a reference point, the average human reaction time is 250 msecs (1/4 of a sec). Their proposed reflex would have to exceed this response. Finally, a subsequent study failed to confirm any difference in the contraction timing of the transversus abdominis and refuted this feedforward mechanism (Morris , Lay , & Allison , 2012).

Although the term "core" had been in use since the 1960's, there had not been a scientific rationale for its spinal function. When transversus abdominis theory was proposed by Hodges, it became popular with the groups that embraced core strengthening, especially Pilates Studios. In addition to their ballet related movements, they promoted exercises that supposedly strengthened the transversus abdominis. Despite the physiologic impossibility of the "feed forward" mechanism, the purported importance of this muscle was disseminated worldwide through the network of Pilates Studios around the world. As instructors, trainers, and therapists began focusing on abdominal flexion exercises for clients and patients with low back pain the term “core” became a universal buzz word. Unfortunately, any emphasis on the spinal erectors began to fade in the general public.

The Missing Link of Lumbar Extension

The Premise of Ligament Support During Lifting

While the torsion advocates had difficulty establishing how lifting force could be generated from the abdominal muscles, the extension proponents were trying to reconcile how lifting occurs when the spinal extensors apparently lacked sufficient force capability during lifting. To solve this riddle, some researchers hypothesized the involvement of non-muscular structures. They focused on the finding that EMG analysis showed less electrical activity during lowering than in lifting. These low amplitude EMG findings led some researchers to postulate that structures other than the spinal erectors were the spinal ligament system.

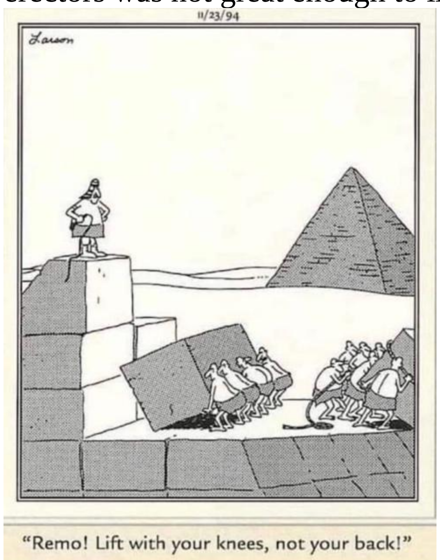
Typically, the recorded muscle signals will increase as muscle contraction intensity increases. However, during lifting it was noted that when the loaded lumbar spine moved from extension to flexion, the recorded EMG signal not only did not increase, but rather decreased. The "flexion relaxation phenomenon" (FRP) was first reported by Swedish researchers Andersson, Ortengren, Herberts, and Schultz in their study published in 1974. Since the spine started in the extended position, the term “relaxation” meant gradual flexion of the spine under load. This flexion was accompanied by a decrease in the EMG signal. At the time, the decreased myoelectric activity was interpreted that passive structures such as the ligaments and joint capsules were bearing the load. Since ligaments could withstand higher loads than muscles and also had no electrical signal, they theorized that the heavy loads were supported during lifting by ligamentous tension.

However, the problem arose that ligamentous structures maintained posterior tension during load bearing does not correlate with the mechanical behavior of the spine as described by Panjabi and White. A critical concept of spinal biomechanics model is the existence of a neutral zone. In order for spinal motion to exist there has to be a range which is not limited by ligamentous restraints. Thus, a broad zone from full flexion to full extension in the spine is unrestricted by ligamentous restraints. At full flexion, the interspinous ligaments, the supraspinous ligaments, the annulus, and facet capsules restrict further bending. The neutral zone, where there is no ligamentous tension, makes up to 70 degrees of the spine’s motion (White A, 1978). Therefore, ligamentous tension alone cannot explain the spinal stability during flexion or extension and does not account for the force required during lifting. It became necessary to re-evaluate the lumbar extensors as the stabilizing force during lifting.

The Role of the Lumbar Extensors During Lifting

An excellent overview of early lifting science was given by Peter Davis in 1959 which summarized many of principles still applicable today (Davis, 1959). He stated that there was virtually an infinite number ways the human body can lift an object but as the load increased the trunk is held in one of two extremes of position: straight or flexed. Since in the neutral position of the low back the lumbar spine is in approximately 40 degrees of lordosis, the “straight or neutral trunk” is actually in partial lordosis.

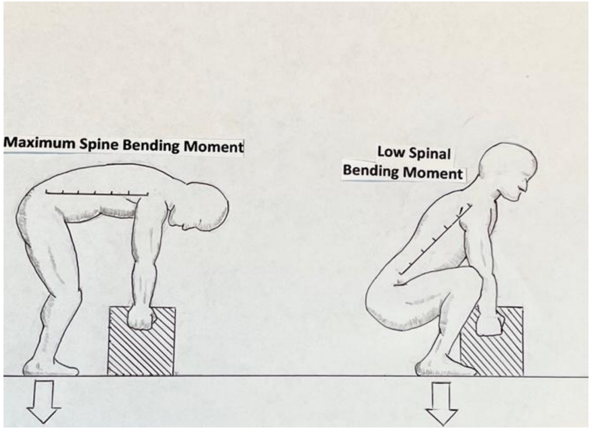
Later studies characterized these positions of the trunk during lifting as either “squat lifting” (trunk straight) or “stoop lifting” (trunk flexed) (Anderson CK C. D., 1985). Although these two postures are distinctly different, they both contain the three major force contributors: the load; the spine; and the trunk muscles. The problem remained that the calculated strength of the spinal erectors was not great enough to lift the loads that were observed in real world lifting tasks.



“Remo” is the third from the left.
(Gary Larson, 1994)

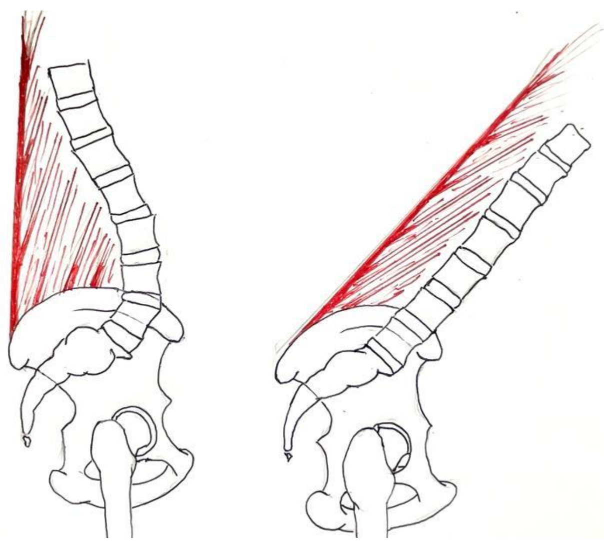
The calculated muscle force must equal the weight of load multiplied by the length of the spine. Early biomechanical analyses examined spinal lifting with the spine flexed and proceeded to the upright posture, which is referred to as the “stooped” lift. The biomechanical analysis revealed two problems with the role of the spinal erectors in stooped lifting. The first was that in stooped lifting the load is held at a far distance from the axis of bending in the spine, creating a moment arm that multiplied the effective resistance of the load. The calculated muscle force required of the stooped lift was not great enough to lift loads routinely seen in the workplace (Cossette, Farfan, Robertson, & Wells, 1971).

On the other hand, the squat lift style involves lifting with the straight trunk (partial lordosis) and bent knees. In biomechanical models the squat lift was found to place the load at a shorter moment arm and the erector spinal muscles maintained a more lordotic (“the straight spine”) posture that moved the pivot point more posteriorly (Cossette, Farfan, Robertson, & Wells, 1971). In the squat lift the load is held significantly closer to the body, thus reducing the moment arm of the load (Morl, Wagner, & Blickhan, 2005).



Thus, although the spine is better positioned to handle the load, the dilemma is that the spine begins in the extended position and does not create an active lifting moment but functions as a fixed lever. Thus, integral to the squat lift is that the major lifting force is generated from the hip extensor muscles which rotate the pelvis posteriorly and the spine remains immobile. It was found that the force is generated by the extension of the hips and knees alone was sufficient to lift the load (Schipplein OD, 1990). In fact, the hip extensors create twice the extension force of the spinal erectors (Seonhong, 2009).

Another critical feature of the lumbar muscles is that their line of pull is drastically different in the flexed forward position than in the extended position. The spine does not function like a pivoting joint, but rather like a bending post. When the spine is flexed, as it is during stooped lifting, the muscles lie parallel to the spine and have poor leverage to extend. However, in lordosis, a line of pull is created that gives the muscles a better advantage. Just like an archer's bow, the spine can be made rigid from the taut bow string of the muscles that traverses it. For this reason, the tensioned, immobile spine in extension is better suited for transmitting loads. As will be shown, if the load exceeds the muscular force, there is a mechanism that is engaged to withstand even higher loads.



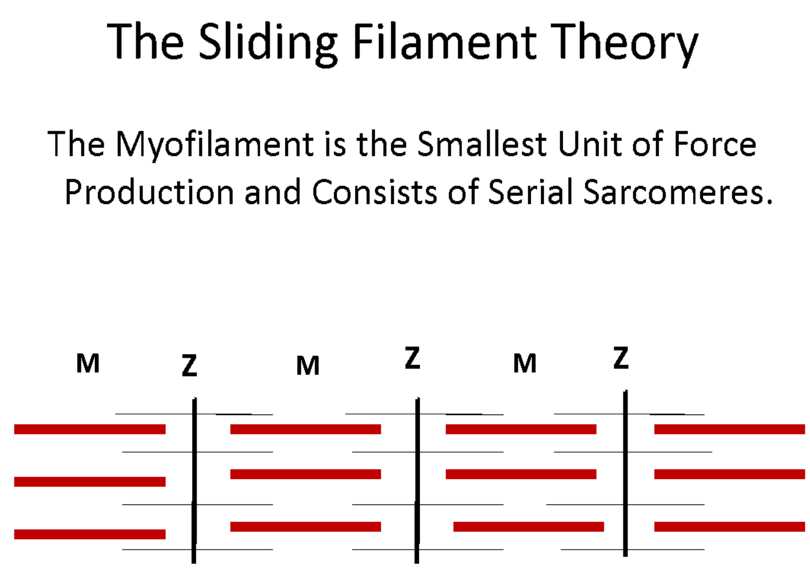
The Duality of Muscle

Because the contraction strength created by erector muscles is not adequate enough to create the observed lifting force, another property of muscle to maintain stability may be employed. This property is what muscles display when they are forcibly lengthened, called “eccentrics”. To discuss eccentric activity, it is necessary review the two different molecular mechanisms of muscle function.

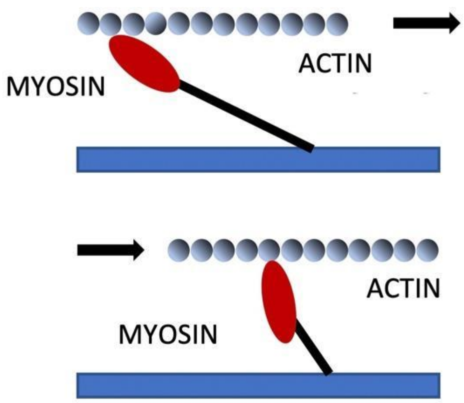
How Muscle Create Force: Concentric Contractions

The mechanism by which muscles contract, the characteristics of muscular contraction, and the level of force created has been thoroughly described over the last 70 years. A brief discussion of normal muscle physiology will be helpful.

Every muscle consists of cells that are aligned within the muscle. These cells are called “myofibers” and each has a nerve ending that delivers an electrical signal to the muscle fiber’s membrane. Each nerve fiber only connects with a limited number of myofibers. The nerve triggers the release of calcium ions into the cytoplasm calcium ions bind and initiate an interaction between opposing molecules on the two strands inside a filament of muscle. These strands are located within each contractile unit within the filament. One opposing strand is called the “thick filament” with its serial myosin molecules. The thick filament is anchored in the middle of the sarcomere at a structure called the “M-Line”, with each half extending towards opposite ends of the sarcomere. The other sliding molecule is called the “thin filament” with its attached actin molecules. There is a collection of thin filaments at each end of the sarcomere, attached to a molecular partition called the “Z-disc”. On cross section, the thin filaments surround each thick filament in a hexagonal grouping. When activated, the pulling of the thin filaments along the thick filaments cause each opposing Z-disc to pull together, thus shortening the sarcomere. Each myofibril consists of thousands of these contractile units called “sarcomeres”, connected in a long series. Each sarcomere is separated from the other by the “Z-disc”.



Muscle activation causes the myosin molecule on the thick filament to bind to and pull itself into alignment with the actin molecule on the thin filament through the formation of a cross-bridge. The myosin head pivots, pulling the thin filament toward the center of the sarcomere. This movement is called the power stroke. The stroke is propagated when energy, supplied by ATP molecules, causes a conformational change in the myosin head causing it to detach and bend towards the next actin molecule along the filament. As the thick and thin filaments are pulled past each other, the sarcomere shortens, creating a muscle contraction. This process is known as the "Sliding Filament Theory". The amount of force a contraction can create depends on the number of myofilaments stimulated.



The ATP powered muscle contraction requires a continuous release of calcium ions to instigate the ATP-myosin interaction. The calcium is released from the endoplasmic reticulum through electrical activation from the motor unit. Thus, concentric contractions exhibit a significant EMG signal when activated. Generally, the more motor units activated the higher the EMG signal.

The Role of Eccentric Muscle Activity

It is not as well appreciated that our bodies are constantly exposed to high levels of external force that can far exceed the contraction strength of the involved muscle. These force levels are so high that they are frequently measured in multiples of body weight. For example, simply walking involves a foot strike which encounters a level of force that is one-and-half times body weight of force. In going down steps, the descending foot must encounter and control up to three-and-a-half times body weight; jumping off a wall creates forces sometimes in excess of ten times body weight. These overload forces are not exclusive to the lower extremities. In the process of forceful throwing, the thrown object first is propelled backwards, stretching the muscles of shoulder with high levels of force. In fact, virtually every sport and human activity encounters forces that exceed the force levels that the muscle itself can generate. This includes the spinal erectors during lifting tasks.

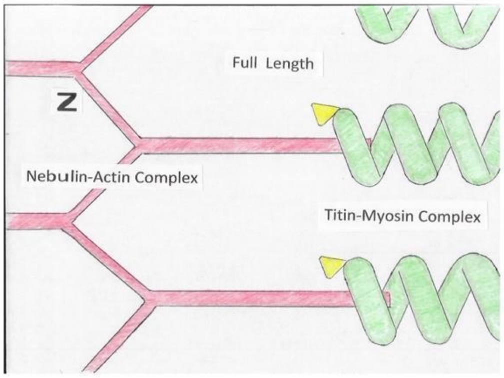
Body Exposed to Supramaximal Forces From Gravity and Momentum

- Walking is 'Falling Forward'----- 1.5X Bodyweight
- Running is 'Jumping Forward'------ 2.5X Bodyweight
- Going Down Steps---------------------3.5X Bodyweight
- Hopping off 1 foot wall--------------- 4.5X Bodyweight
- Foot Plant for Jumping---------------- 7.0X Bodyweight
- Windup and Throwing--------------Eccentric Recoil
- Baseball and Golf----------------------Back Swing

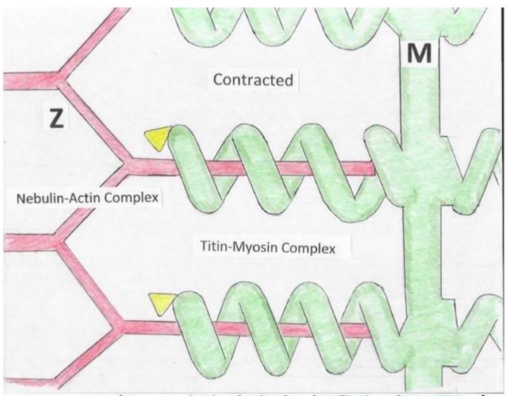
An important characteristic of eccentric muscle activity is that it is not under conscious control. The response to these excessive overloads is reactionary and occurs at the molecular level without neurologic input. Just as the shoulder harness in a car's seatbelt engages automatically when a sudden pulling occurs, the eccentric muscle action responds to sudden forced lengthening in the muscle.

To protect against this overloading, there exists a mechanism that is brought into play to utilize the large elastic molecules within the myofilament. When these molecules are engaged and stretched, it is called "eccentric lengthening". Depending on the muscle, eccentric muscle force can resist up to 80% more applied load than it can generate itself (Lieber & Friden , Mechanisms of muscle injury after eccentric contraction 2(3), 1999), (LaStayo , et al., 2003). The following discussion describes how the intracellular contractile elements (actin and myosin) connect to and engage an intracellular and extracellular cytoskeletal support system to allow the muscle resist very high levels of mechanical tension and transmit it to the remainder of the musculoskeletal system.

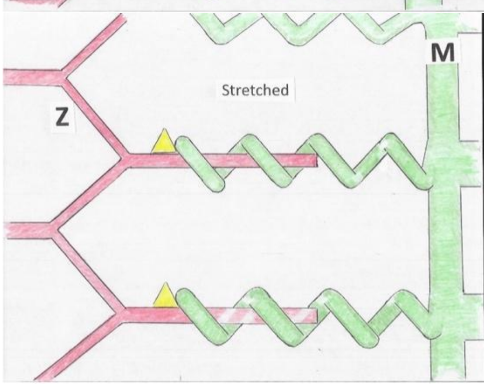
This lengthening eccentric mechanism was proposed in 2011 with an elegant theory that explained the role of titin and nebulin as a mechanism for protecting muscles from overload forces called the "Winding Theory" (Nishikawa KC et al 2011). Titin is the largest molecule in the human body and completely spans the sarcomere in human muscle. It extends from the M-line towards each Z-line. Titin is the primary molecule of the thick filament (hence the name) and as such provides the attachment points for the myosin molecules. Likewise, the thin filament's structural molecule is called "Nebulin" and also has elastic properties. Just as titin carries the myosin molecules, nebulin has the actin molecules attached. The Winding Filament Theory reminds us that they are not two straight filaments laying side-by-side, but rather the molecules have a helical structure and intertwine with each other. The nebulin molecule originates on the Z-disc and the titin molecule inserts there through another structural molecule, desmin, at the Z-disc (Paulin[1], Li, Exp Cell Res, 2004).



Muscle at Length:
Requires that Actin and
Myosin pull Titin-Myosin
Along Nebulin-Actin to
Shorten the Muscle



Muscle has Contracted
by Titin-Myosin "Sliding"
along Nebulin-Actin



Sudden Stretch causes Titin to
Latch onto Nebulin and the
Maximal Load is 'Resisted' by
Titin elastically stretching
while transmitting
the high force to the
Tendon, Bones, and Ligaments

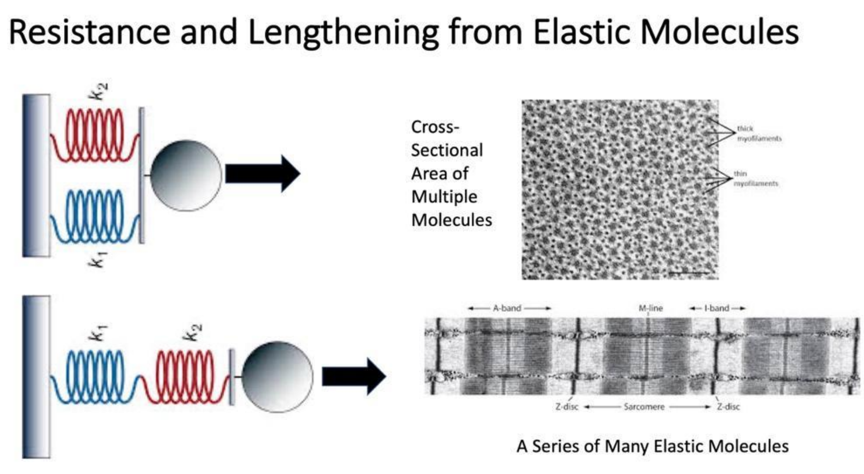
Lengthening of the Maximally Stimulated Muscle

When placed under a light load, maximal stimulation of the muscle results in high shortening velocities. As the applied weight increases the maximum shortening velocity of the muscle decreases. Finally, the amount of external load tensioning equals the maximal contractile force of the muscle. At this point, the tension prevents shortening. With the thick and thin filaments being pulled apart, the myosin molecule cannot detach from the actin molecule, thus locking the thick and thin filaments together. To prevent damage to the filaments, the tension across the actin-myosin bond is transferred to the large, elastic titin and nebulin molecules, causing them to stretch. Thus, the heavy, external overload is now transferring its force into elastic energy stored in the titin and nebulin molecules. Whereas the process of concentric contraction is highly energy dependent, this elastic sarcomere lengthening requires very little ATP for energy. For this reason, a lower level of motor unit activation is needed during eccentric lengthening which accounts for a lower level of EMG signal during eccentrics.

If the actin and myosin molecules of the eccentrically active muscle are ‘locked down’ and unable to detach, how does the muscle lengthen under overload conditions? The answer is that the muscle no longer lengthens by filaments sliding past one another, but rather by elastic stretching of the large titin and nebulin molecules.

The elastic elongation follows the principles of spring deformation as described by Hook’s Laws. Hook’s first law states that elastic structures connected in a series, like rubber bands looped end-to-end, can be stretched a much longer distance than just a single elastic element itself. Since there are innumerable sarcomeres connected together, there can be substantial stretch of the sarcomeres to allow muscle lengthening, even without sliding of the actin and myosin molecules past each other. The elastic elements can also resist a large amount of external load according to Hook’s second law. This states that elastic elements arranged in parallel will combine to resist very high external force. This arrangement in parallel is exactly how myofibrils are arranged in cross section. Again, since there are a large number of myofibrils in the cross section of a muscle, there can be considerable resistance available to withstand overloading. Thus, lengthening during overload arises from the elastic elements in series, yet strength is maintained from the elastic elements in parallel.

Parallel = Strength



Series = Length

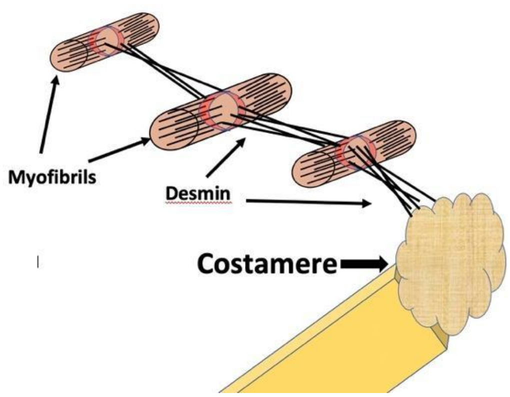
The Intracellular Cytoskeleton and the Extracellular Matrix

The Cytoskeleton

If each myofiber has its own motor nerve and not all myofibers are activated at the same time, it would appear that muscle contractions would be disjointed by some myofibers shortening while others were left at their longer length. However, there exists an intracellular molecular framework that binds the myofibrils together to permit coordinated movement of the contractile elements.

The first molecule that connects to the cytoskeleton is via a molecule called “Desmin”. Desmin plays a crucial role in maintaining the structural integrity of muscle fibers during contraction. Desmin filaments link the Z-disks of adjacent myofibrils, ensuring their proper alignment and coordinated contraction within the myofiber. This distribution of the force to adjoining myofibrils is called “lateral force transmission”. This network distributes the mechanical stress generated during contraction to the cell wall or sarcolemma. Through their connection to the sarcolemma, the myofibrils within the muscle cell communicate with an extracellular matrix of structural proteins. The intracellular cytoskeleton is attached to the cell membrane by a structure called “the Costamere”.

Costameres receive the lateral force generated by myofibrils and transfer it to the extracellular matrix by connecting muscle fibers to the extracellular connective tissue (discussed in next section). The dystrophin-glycoprotein complex (DGC) is a key component involved in this force transmission. Dystrophin, a cytoskeletal protein, connects actin filaments to a glycoprotein complex, which spans the sarcolemma and interacts with extracellular proteins such as “Laminin”. This complex stabilizes the sarcolemma during muscle contraction and protects it from injury. Thus, the muscle’s intracellular components connect to the extracellular environment in order for its mechanical force to be shared by the extra-cellular matrix.

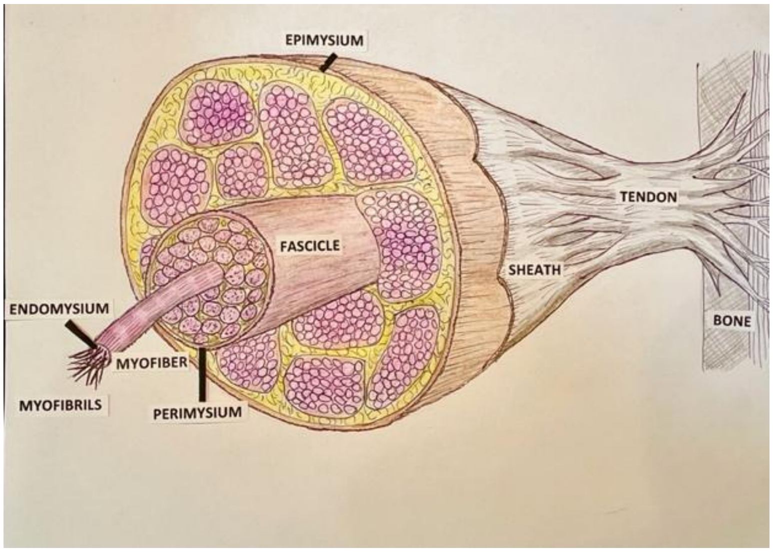


Extracellular Matrix

It has been shown how the force coming from within the myofiber connects into the costamere. This molecular complex transmits the internal force to a collection of extracellular, fibro-collagenous fibers, collectively known as the “Extra-cellular Matrix (ECM)” (Lieber RL, Meyer G.J Biomech. 2023). This network receives the force transmission originally from the myofibrils within the myofiber, and transfers it to the extracellular system called the “Endomysium”. These external fibers interconnect with the endomysium on the adjacent muscle cells. Thus, a large group myofibers become bundled together in a larger collection called a fascicle. The fascicle is, in turn, surrounded by its own ECM called the “Perimysium”. Next, all the fascicles themselves are bundled together to form the entire muscle. Finally, too maintain force continuity, all of the fascicles are surrounded by their own layer called the “Epimysium”. This also part of the ECM and as such continues the role of carrying the muscle force into the musculotendinous system.

These investments around the contractile elements function very similar to the woven covering around a bungee cord. When stretching causes a muscle's rounded shape becomes more elliptical, the muscle sheaths tighten and contributes significant resistance to the force pulling on the muscle. It is only through the contribution of ECM and tendon sheath can muscles eccentrically resist the extremely high loads to which they are exposed.

Thus, the force of the intracellular myofibrils has a continuous pathway from the cytoskeleton, through the costamere, and into the ECM. This transmission system through the entirety of the ECM is capable of transmitting much higher levels of force than the muscle itself can generate.



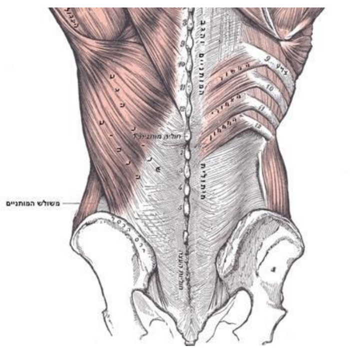
The Myotendinous Junction

The final contribution for force transmission does not arise solely from the muscle itself, but rather also from collagenous fibers that are received from the tendon. These tendinous extensions attach to the epimysium and spread out evenly around the entire muscle to form what is commonly called the muscle sheath. At each end of the muscle, the muscle sheath coalesces into a single, strong, collagenous cord that becomes the tendon.

The size and shape of the myotendinous junction is adapted to level of tension it has to withstand. Muscles that function mainly for mobility and are rarely called upon to withstand high external loads typically have relatively little surface area at the musculotendinous junction. In contrast, there are the large muscles that have "anti-gravity" or force absorbing function. These muscles dissipate the high external force levels by spreading the attachment over a large area.

Examples of this include the biceps and triceps muscles of the upper arm. The biceps, in normal use, are not subjected to heavy overloads. The biceps muscle therefore has a smaller diameter tendon with a myotendinous junction that has a limited area of attachment. In comparison, the antagonistic triceps has a tendinous attachment the spreads over a wide flat area called an "aponeurosis". The triceps is involved in high force situations such as falling on the outstretched arm or pushing the body up from the lying position. Similarly, the hamstring muscles are called upon to eccentrically slow the rapidly accelerating low leg during running. While sprinting, the low leg can accelerate up to 1500 degrees per second. If not decelerated by the hamstrings, the momentum of this movement could snap the knee into hyper-extension. Therefore, the hamstring muscles also have tendons that resolve into wide attachments to manage this force. This is exemplified by their names, such as the semimembranosus and semitendinosus. This adaptation is so consistent is that you can predict a muscle's function by the surface area of the myotendinous junction.

Therefore, because of their function, the spinal erector muscles are well suited anatomically to withstand eccentric overloads. The largest expanse of myotendinous surface area in the human body is called the 'lumbar aponeurosis'. This thick, broad fascial area covers the majority of the lumbar spine and receives attachments from four of the five groups of the spinal erectors to form the thoracolumbar fascia. It proceeds to fan out and insert upon the thorax above to dissipate overload forces.



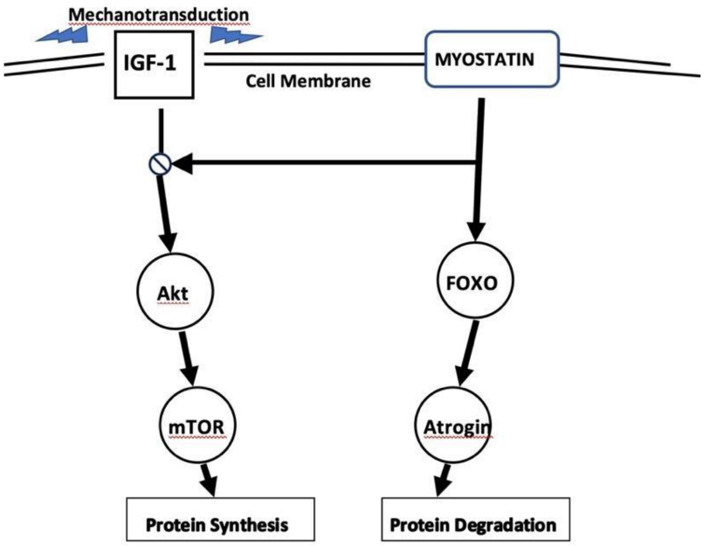
The Hypertrophy Stimulus

Mechanotransduction

As the interface between the intracellular contractile elements and the extracellular matrix, the costamere is uniquely positioned to monitor and respond to the various levels of force experienced by the muscle. Thus, the costamere complex serves to detect the amount of mechanical strain the muscle is exposed to.

Since muscle mass requires protein synthesis, which is highly energy dependent, only the amount of muscle mass that is needed is maintained. This is accomplished by constantly balancing the anabolic growth and catabolic breakdown of muscle protein. The extent to which one process dominates over the other is determined by the amount of force sensed in the costamere. The costamere receives mechanical signals from the sarcolemma of the muscle cell, the Z-discs of the myofilaments, and its connections to the extracellular matrix. When force transmitted through the muscle is high enough to stress the cytoskeleton, the costamere senses the deformation and signals the elaboration of a factor called IGF1(Insulin-like Growth Factor). Through a cascade of intracellular molecules, IGF1 ramps up the synthesis of contractile proteins and the cytoskeletal elements.

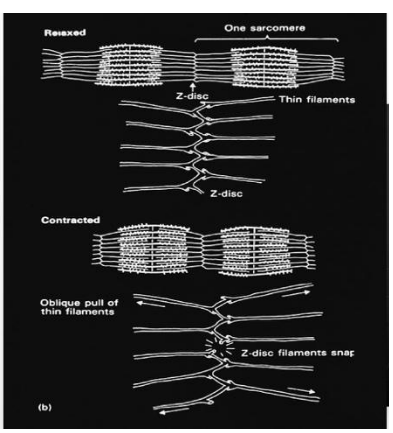
Conversely, the absence of any mechanical force sensed by the costamere is a signal to reduce the structural and contractile elements of the muscle, the "use or lose it "principle. The key signaling molecule for decreasing protein synthesis is called "Myostatin". This has a significant effect to not only decrease protein synthesis, but also to increase the activity of pathways which degrade existing contractile proteins. The cessation of protein synthesis and the dissolution of existing contractile proteins can cause a marked reduction in muscle mass. Muscle mass loss can be a more rapid process than growth of muscle mass.



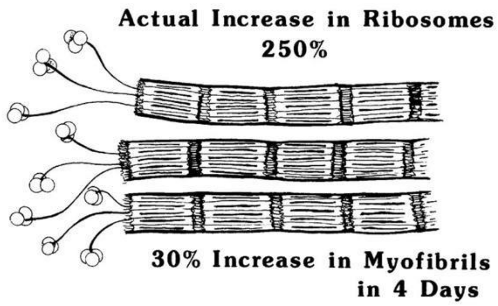
Under normal loading conditions the costamere balances muscle homeostasis to accommodate to the forces detected. But, there are circumstances where extreme mechanical tension that threatens the mechanical integrity of the myofiber and trigger a much stronger physiologic response.

Repair and Regeneration

There are loading conditions which exceed the structural limits of the muscle's cytoskeleton. As the external load applies higher and higher tension through the cytoskeleton, it eventually reaches this structural limit and separations inevitably appear. Since both titin and nebulin attach to the Z-disc, this is the focus for these micro-tears. Tissue disruption initially elicits a non-specific inflammatory response followed by a reparative process.

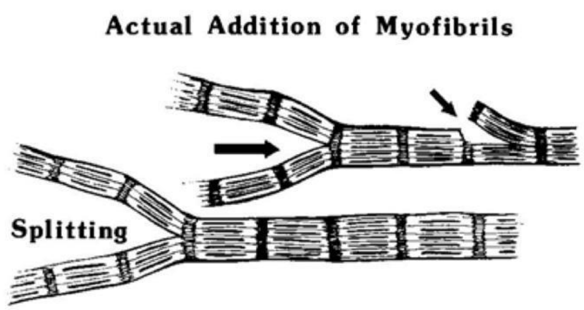


The focus of the repair response is at the Z-disc where the myofibrils and their cytoskeletal elements are damaged. These strands of molecules become the site at which, not only can the elements be repaired, but also become the site to add filaments to increase the size and strength of the muscle. The additional myofibrils within a muscle cell can incorporate into the contractile continuum through branching. Sarcomere branching can occur either through splitting of a single sarcomere into two or through the creation of a new myofilament between two adjacent sarcomeres. (Willingham, TB; The unified myofibrillar matrix for force generation in muscle Nature Communications volume 11,2020).

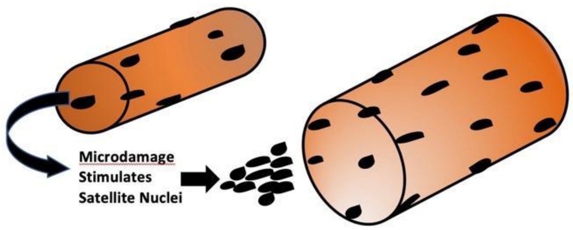


Cameron-Smith D. Exercise and skeletal muscle gene expression. Clin Exp Pharmacol Physiol 2002; 29: 209-213.

Tissue damage increases local blood supply and attracts migratory inflammatory cells to the injured area. This inflammatory phase is widely considered to be source of delayed onset muscle soreness (DOMS). This is followed by large increase in nuclear protein synthesis to repair the damaged cytoskeletal elements. Finally, additional myofilaments are created by building branching chains of new myofilaments. These new filaments and the subsequent myofibrils, are the basis of muscular hypertrophy.



The costamere plays another important role in repair and regeneration as well. The hypertrophying muscle requires the support of additional nuclei to provide the machinery of protein synthesis. Costameres signal the satellite cells that lie just inside of the muscle cell wall to activate and migrate to become active mature myonuclei. They serve to support and maintain the additional myofibrils. The end result of the overload stimulus is a larger, more resilient muscle with additional myonuclei.



The Spinal Erectors as Eccentrically Active Muscles

There are three characteristics of the spine muscles during heavy lifting that indicate they are functioning eccentrically: 1) they prevent spinal bending under supramaximal loads; 2) they can function for long durations with little required energy; and 3) they demonstrate reduced myolelectric activity during forced muscular lengthening.

The ability the spinal erector muscles, in particular, to function as “springs” under external loading has been theorized for years. In 1995 it was noted that the amount of muscle stiffness required to maintain posture under load was well above what had been previously theorized based on measurements of back muscle strength. Since the force levels required were so high this study stated that “These findings support the hypothesis that activated muscles must behave as springs and not just force stabilizers…” (Gardner-Morse, Stokes, & Laible, 1995). The ability of muscles to behave as “springs” has long been noted in physiologic literature but until recently the molecular basis of passive tension in lengthening muscles has eluded researchers (Lindstedt, Reich, Keim, & LaStayo, 2002). The first researcher to invoke eccentric muscle activity for the spinal erector muscles during lifting was Shu (2008).

The other conundrum was the reduced EMG signal during lowering tasks under load. Muscles can withstand more force with less activation during eccentric actions compared to concentric actions: “A wealth of literature exists indicating that EMG amplitude during concentric contractions is greater than that of eccentric contractions of the same magnitude” (Journal of Electromyography and Kinesiology 18, 2008). This is because during eccentric lengthening, the elastic molecules within the muscle are not producing force but rather restraining a high, externally applied load. It is the passive stretching of the nebulin-titin molecules that withstands the excessive tension of a supramaximal load. Thus, the flexion-relaxation phenomenon noted during lifting can be explained by the role of eccentric tension of the spinal erector muscles. The position of the muscles, their electrical silence, and their increased force capabilities are all consistent with the observations of the flexion-relaxation phenomenon.

Therefore, the primary role of the lumbar extensor muscles can be summarized in one sentence: *“In lifting, the lumbar muscles do not extend the spine, they prevent the spine from flexing.”*

Clinical Considerations of Eccentric Training

Once the acute symptoms of back pain have resolved and it is determined that the lumbar spine is mechanically competent, strengthening of lumbar muscles can begin, albeit in a slow progressive fashion. Lumbar strengthening “enhances the structural integrity of the lumbar spine through progressive loading and improves the metabolic exchange of the lumbar discs through repetitive motion” (Mayer 2008). Additionally, educational strategies to avoid painful activities, promote weight loss, increase general fitness, and reinforce lifting form are important adjuncts to treatment. In addition it is important for those of advanced age to regularly place the spine through a full range of motion to prevent loss of spinal motion Thus, lumbar muscle strengthening is a critical intervention to reduce pain from degenerative instability, but is also part of a more comprehensive treatment program.

Maintaining the strength of the low back and more specifically targeting the eccentric function of the lumbar extensors is most beneficial to maintain lumbar function during aging. Below is a list of benefits that can be accrued from strengthening of these muscles and specific conditions that can be addressed.

Injury Prevention

The role of muscular force in maintaining lumbar integrity was described by White and Panjabi (White & Panjabi, 1971). They showed how such forces as compression, lateral bending, and flexion worked in conjunction to protect the spine. Their testing protocol applied force across the spine which replicated muscular tension, called “Preload”. Using coupled motions and forces, they demonstrated how the muscles, ligaments, discs, and bony elements relied on one another to provided support. For example, muscular compression under conditions of torsion or extension caused the facet joints to become mechanically engaged. Thus, spinal rotation or extension under compression was 150% stiffer than without muscular pre-load because of the engagement of the facet joints.

One caveat is to carefully control the load applied while the spine is flexed to guard against disc injury. As the spine goes into flexion, there is a twofold effect on increasing the disc pressure as the spine bends. First, there is a reduction of facet contact which puts all the force on the disc itself. Second, the moment arm through which the load is applied becomes more perpendicular to the spine and exerts a higher force (White A, 1978). If the spine is forced into flexion, there is typically some simultaneous distraction of the posterior spine during flexion. This distraction force affects the posterolateral corner of the intervertebral disc and, when of sufficient magnitude, can produce a herniated nucleus pulposus (Adams & Hutton, 1982).

In extension predominant axial failure mode of the lumbar spine is vertebral endplate fracture (Rolander & Blair, 1975). Fortunately, the vertebral bodies are strong and when loaded to failure and can resist 3-4000 Newtons of force (Shirazi-Adl, Shrivastava, & Ahmed, Stresss Analysis of the lumbar disc-body unit in compression:A three-dimensional nonlinear finite element study. , 1984). These studies reinforce the importance of the lumbar extensor muscles maintaining the spine in lordosis during heavy lifting.

Thus, a major role of the spinal erector muscles is to maintain the spine in lordosis during lifting. This tension created by the lumbar extensors engages the facet joints to unload the disc pressure. Under high loads it is the eccentric function of the spinal erector muscles that maintains a contracted position to prevent lifting injuries.

Lumbar Disc Degeneration and Kyphosis

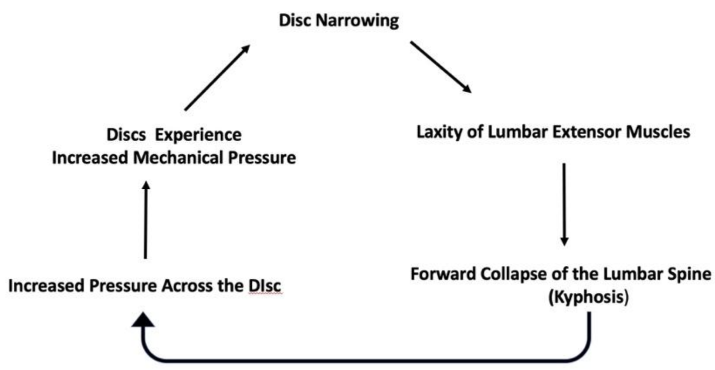
The primary age-related disorder the lumbar spine is the inevitable narrowing of the lumbar discs. Through the process of aging, the entire lumbar spine can lose 20 – 40 mm of height. In healthy, young discs, intermittent loading is an important mechanism for the nutrition of the cells in the nucleus pulposus, functioning like a pump to deliver nutrients and expel waste products. However, through the process of programmed cell death during aging (apoptosis) or injury, there is the loss of fluid within the disc. The resulting disc height loss adversely affects spinal stability by allowing excessive vertebral motion to take place. Compounding this, the disc space narrowing occurs predominately in the anterior portion of the disc, thus causing the spine to tilt forward. The resulting straightening of the lumbar spine is called "kyphosis". By causing a further anterior shift of the body's center of gravity, kyphosis further compounds disc height loss. This sets up a cascade of events that worsens the condition. Lumbar kyphosis is the predominant cause of losing the upright posture and decreases the ability of the patient to walk, stand, lift, and carry.

Aggravating this problem is sarcopenia or loss of muscle mass with aging, which affects the lumbar extensors just as it does the rest of the muscles in the body. Since sarcopenia occurs approximately during the same period as disc degeneration, it weakens the ability of the lumbar extensors to prevent kyphosis and stabilize the unwanted motion between the vertebra.

Another, less recognized result of multi-level disc narrowing is that the lumbar muscles lose their optimal resting length, which reduces the ability to generate force. Although this is yet another blow to lumbar muscle strength, muscles can re-adjust their resting length over time. The classic example is when patients are left in bed without ankle support and the gastrocnemius muscle, within days to weeks, can actually become fixed in a shortened position. The calf muscles can restore their strength at the shortened length. The shortened lumbar muscles, likewise, can re-tension and restore function of the shortened lumbar spine. One role for lumbar supports are those episodes where the spine has shortened but muscular compensation has not yet occurred.

Osteoporosis

The disc is not the only spinal structure that changes with aging. Since muscular force is the primary stimulus for bone density, the loss of muscle mass also is associated with decreased bone mass in the spine. With lumbar muscle weakness, the body mass tilts anteriorly and compressive loading of the lower density vertebral bone is increased. Thus, any forceful exertions or loading would pose a risk of vertebral compression fracture. Unfortunately, this further worsens the cycle as the center of body mass shifts even further anteriorly.
The result of these changes is the tendency of elderly to lean forward during walking and standing. This process is insidious and begins in the fourth and fifth decade. The only intervention which could counter this cycle of weakness causing kyphosis is to maintain or increase the strength of the spinal erector muscles.



Low Back Pain

"Back pain" is a ubiquitous term used to describe discomfort or discomfort felt anywhere along the spine, from the chest down to the lower back. It's a common complaint, with up to 80% of individuals experiencing it at some point in their lives. While it is indeed a symptom rather than a diagnosis, its widespread usage in medical research reflects its clinical significance as a common presenting complaint in spinal conditions. Researchers adopt this term for its clinical relevance, accessibility, diagnostic flexibility, holistic perspective, and utility in evaluating treatment outcomes. Disc degeneration and low back pain share many of the same causes and treatments.

Despite few studies giving specific, structural diagnoses in their chronic low back pain subjects, the causes of low back pain arise from loss of internal disc pressure, disruption of the annulus, and degeneration in the facet joints. Under normal conditions these structures are responsible for bearing the large compressive forces during lifting. If patients have disc degeneration or facet arthritis, the lack of stability from muscular support can aggravate spinal symptoms. According to the 2008 Mayer review in The Spine Journal; "In CLBP [Chronic Low Back Pain] patients, the lumbar extensors are weak, highly fatigable, atrophied, display abnormal activation patterns, and exhibit excessive fatty infiltration and histopathological changes". It has been well documented that the excessive motion caused by instability can not only be symptomatic, but also instigates the arthritic process. By managing the degenerative instability through lumbar strengthening, the painful symptoms may resolve over time and eventually the vertebral tissues can respond and re-stabilize the segment (Carpenter DM, Low back strengthening for the prevention and treatment of low back pain. Med Sci Sports Exerc, 1999)**.**

However, patients with advanced degeneration, segmental instability, significant loss of spinal alignment, or defects such as spondylolisthesis should have an entirely different strategy of treatment. Failure to tolerate gradually increasing resistance training of the spinal musculature may be indicative of poor mechanical integrity of the lumbar spine. Ultimately these patients may benefit from carefully planned surgery, to restore the mechanical integrity of the spine.

Thoracic Kyphosis

In the absence of congenital, developmental, or traumatic conditions that can present earlier in life, kyphosis in the thoracic spine usually occurs in a much older population. This is largely because of the stability of the thoracic spine imparted by the rib cage. The ribs are firmly attached to the vertebra and posterior elements of the thoracic spine and then (with the exception of the twelfth rib) are connected to the sternum anteriorly. For this reason, the thoracic spine functions effectively as a single unit with little movement between the vertebra themselves. Although in young adults, spinal exercises and pressure application at the apex of the kyphosis can reduce the amount of postural kyphosis (Tarasi Z, et al. The Effect of Spine Strengthening Exercises and Posture Training on Functional Thoracic Hyper Kyphosis in Young Individuals. J Adv Med Biomed Res 2019), the rigidity of the thoracic spine means that the posterior spinal erector muscles have much less effect on the contour of this spinal segment. Although exercises to strengthen the thoracic posterior musculature are not particularly effective in combating kyphosis, resistance exercises of the upper back muscles can address some of the associated symptoms that come with thoracic kyphosis.

Adult Onset Scoliosis

The onset of scoliosis in the previously normal adult spine mainly originates in the lumbar spine. This condition often develops due to degenerative changes in the spine, such as the deterioration of the intervertebral discs and facet joints. As these structures lose competency, kyphosis and instability can occur as discussed above. When intervertebral discs degenerate with age, they lose height and can shift, leading to lateral displacement of one vertebra on another. Degeneration of the facet joints can exacerbate instability and cause asymmetrical loading which can initiate a spinal curvature. Once curvature of spine begins, absent any intervention, gravity can lead to increasing deformity. The dynamic stability afforded by the erector spinal muscles can combat increasing deformity in the lumbar spine by maintaining a posterior tension band, re-engaging the facets and posterior column, which in turn decreases segmental instability.
Thus, this pathophysiology of adult onset scoliosis involves a combination of anatomic, degenerative, and patient-specific processes. Progressive degenerative changes lead to degenerative instability and asymmetry in the vertebral column. Any tendency towards lateral translation of one vertebra over another can instigate the scoliotic process. Maintaining a strong posterior tension band may forestall and hopefully prevent the onset of adult scoliosis.

Basic Principles of Eccentric Spinal Strengthening

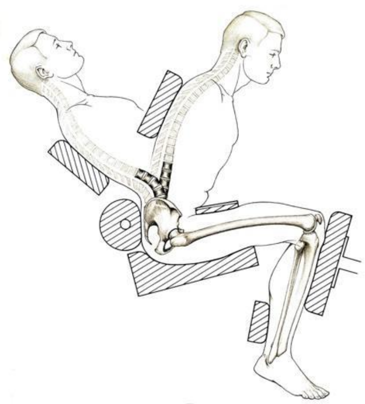
Isolating the Lumbar Spinal Erector Muscles

As part of the posterior chain of muscles, the lumbar spine is subjected to the forces created by the other, sometimes more powerful muscles with which they are connected. For medical resistance training it is important to prevent the lumbar spine from being subjected to these higher force levels.

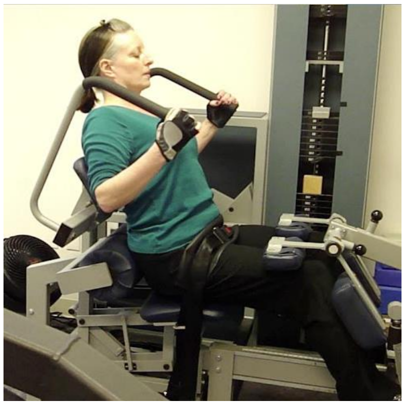
There are two important issues with the function and location of the lumbar muscles. First is that despite having a significant cross sectional area they are closely attached to spine and exert force through a small moment arm. The other issue is the motion of the spine, which does not pivot around an axis, but rather displays a quasi-bending movement. With forward bending, the muscles drape over the spine which makes it difficult to create an extension force. However, in the neutral, lordotic position the muscles have an advantageous, bowstring angle with which to exert force. The clinical relevance is that in the forward flexed position the lumbar extensors are unable to counteract heavy spinal loading which puts the lumbar spine in jeopardy.

The other issue is that the lumbar spine sits atop the pelvis. When the pelvis is extended posteriorly by the gluteus maximus muscles the lumbar spine is also pulled posteriorly. The extension force created by the gluteus maximus muscles can be 2.5 times greater than the extension force that the lumbar spinal erectors can generate. If the subject is bending down to lift a heavy object and the hips forcefully extend, the lumbar muscles may be forcibly stretched by the extending pelvis. The point being that it is the larger gluteal muscles exerting force through the weaker lumbar muscles increase the risk of lumbar injury.

The fact that the lumbar muscles are the 'weak link' during a whole body lifting motion is also an important consideration when training frail, deconditioned, or patients in rehab. In order to avoid subjecting the lumbar spine to potentially injurious muscular forces, the lumbar extensors should be trained in a separate, individual movement. Isolation of lumbar extension essentially means eliminating the extension force of the pelvis and reduces the chance of lumbar injury.
For this reason, the MedX corporation (Ocala Florida) designed an isolation method in which the patient is in the sitting position. The primary way their system blocks pelvic extension is to place a pad against the posterior, flat area of the pelvis. If the patient extends backwards the pad would prevent pelvic extension.



The other requirement is then to prevent the patient from sliding forward from pressure against the pelvic pad. To resist this forward sliding a pad was placed firmly against the upper tibia which by pressing the femur into the hip socket completely locks the pelvis in place. Finally, a movement arm was placed against the thoracic spine which applied resistance. When the patient pushed backwards against the movement arm only the lumbar spine would extend. The pelvis was kept from flexing forward by the muscular force of the gluteal muscles trying to extend but prevented by the posterior pelvic pad. In this position about 70 degrees of lumbar motion is allowed from full extension to full flexion (Leggett SH, Pollock ML, Graves JE, et al. Quantitative Assessment of Full Range of Motion Lumbar Extension Strength. Med Sci Sports Exerc 20:S87. 1988). This restraint system was incorporated into a selectorized, weightstack machine for traditional strengthening of the lumbar spine.



Beginning Lumbar Extensor Training

It goes without saying that lumbar strengthening to counteract the effects of aging necessarily requires a long-term commitment. Standard isotonic resistance, where one set of exercise to failure is done, is known as High Intensity Training (HIT). This program has been documented in relieving the symptoms of low back pain in just 10 weeks (Risch SV, Lumbar strengthening in chronic low back pain patients. Physiologic and psychological benefits. Spine, Feb 1993). However, to prevent the age-related decay of function, strengthening should be maintained for years. Thus, making training as efficient as possible is critical to ensure long-term participation of the patient.

To begin isolated lumbar training the patient should be cleared by their physician to participate in strengthening, and have no lower extremity conditions that prevent them from sitting in the exercising position. If the patient can sit comfortably in the exercise position, the next requirement is to guide the unweighted movement arm through a gentle range-of-motion from extension to flexion. Flexing forward should be controlled by the patient and no effort to force the patient further is necessary. Likewise, extension is merely the patient leaning backwards within their comfort level. In those patients who are severely deconditioned or fearful of any movement (kinesiophobic), the first level of training would be to simply to go through the range of motion in the first few exercise sessions and see if there is an improvement of the range. If the patient has low back symptoms during the range of motion testing, progression to weighted exercise should not be done. Also, the patient should be alerted that low back soreness for one to three days after training is common and expected. The most common 'red flag' sign would be a patient that has radiating leg pain or neurologic symptoms that occur during exercise, particularly when the patient is in the extended position. Radicular pain, in general, and is an indication to be evaluated by a spinal specialist. Although, resistance training will be discussed, patients should also be encouraged maintain spinal and lower extremity range of motion through ancillary activities such as yoga, group exercise, and supervised stretching classes (for joint movement).

In patients who are ambulatory and independent, lumbar strengthening can begin with conventional resistance protocols. The benefit of the selectorized weight stack is the use of "progressive resistance". This method recognizes that even for less active, non-exercisers there is some low level of resistance, no matter how little, that can be used as a starting weight. Once initiated, the patient will perform 10 repetitions of the concentric weight, raising it at 2 second cadence and lowering it at a four second count. Once the full 10 repetitions can be done to the point of momentary muscular failure, an approximately 10% increase in resistance can be added. This sequence is continued as long as the patient is making regular resistance gains every few weeks.

Begin Enhanced Eccentric Resistance When Clients Plateau

However, it is expected that progress eventually slows and usually by one year the patient will no longer be making any meaningful increases in resistance (Steele et al, Long term time course of strength adaptation to minimal dose resistance training: Retrospective longitudinal growth modelling of a large cohort through training records. SportRxiv Preprint, 2023). There are two reasons to add a stimulus for additional muscular growth. The first is that deconditioned or rehabilitation patients will often reach a plateau at a relatively low level of resistance because of their starting low level of muscle mass, fear of pain, or lack of spinal mobility. Strengthening beyond this initial plateau is important to try to develop the patients “reserve” strength in case of circumstances that can weaken them in the future, such as sarcopenia and illness. Secondly, the lack of progress is a common reason for clients to stop their training. Using the same amount of weight for a long period time can give the impression that the program is no longer working or simply cause the patient to lose interest.

One strategy for an added stimulus is having the patient do separate, additional sets of training with the same concentric level of resistance. This is known as increasing the “volume” of exercise. One downside of this approach is that this would require additional time and effort at the same level of resistance they have already achieved. Additionally, the improvements in multiple sets training are more likely to be increases in muscular endurance and exercise tolerance, rather than increased strength. To breakthrough this early plateau, an emphasis on strength is preferable.

Eccentrics Can Improve Progress and Promote Adherence

Traditional progressive resistance exercise is effectively a negative feedback loop: when you achieve your target reps; the weight is increased for the next workout and you do less reps. The cycle is repeated until very slow or no progress in achieved. However, once the progressive resistance of concentric muscle strength reaches a plateau, further progress in strengthening can be obtained through progression of the eccentric resistance. Eccentrics can take the patient beyond the plateau.

As was stated, the long-term application of HIT training produces strength adaptation as early as the first 12 weeks (30-50%) followed by slow progress thereafter (Steele et al, Long term time course of strength adaptation to minimal dose resistance training: Retrospective longitudinal growth modelling of a large cohort through training records. SportRxiv Preprint, 2023). It was suggested that “over time greater volumes of training are required to ensure continued adaptation”. Obviously, the additional effort created by this work is one deterrent to program adherence. Thus, by providing a higher load with less effort, eccentrics reduce one of barriers for patients to train their lumbar extensor muscles.

Another advantage of eccentric training is that cardiorespiratory stress is significantly lower than during concentric training. In performing eccentric spinal erector muscle training, this low cardiometabolic demand requires less effort on the part of the patients. When patients are subjected to equivalent workloads of eccentric resistance, heart rate, blood pressure, oxygen consumption and perceived exertion are all significantly lower than concentric training (Vallejo AF, Age and Ageing, May 2006).

Also, eccentrics provide a new stimulus for the growth and restoration of additional contractile tissue. This process goes above and beyond merely resetting the balance between anabolism and catabolism of existing muscle and enters into the realm of "repair and regeneration". Whereas the homeostasis of contractile proteins can occur at even low levels of resistance, micro-disruptions created by high mechanical tension stimulate a regenerative process which promotes the hypertrophic remodeling of the targeted muscles. The practical advantage of this process is that a longer recovery period, of at least one week and in some individuals, as long as two weeks, is required between bouts of supramaximal eccentric training. Thus, patients can get a hypertrophic response with at least one exercise bout a week with a lower perceived effort than conventional training.

Isometric and Isotonic Eccentric Resistance

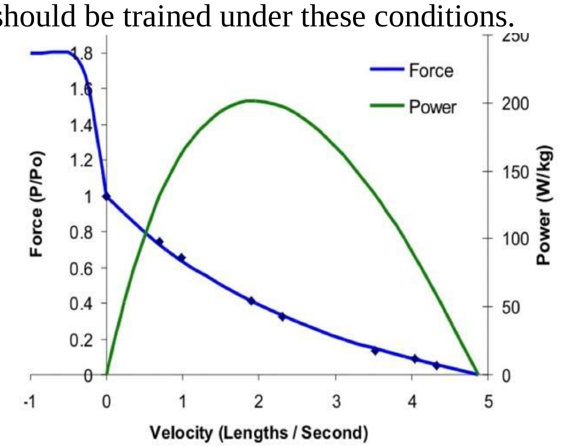
Yielding versus Pushing Isometric Muscle Actions

There is a strong rationale to train the lumbar extensors isometrically. It was shown in the biomechanical studies discussed previously, that the lumbar spine functions isometrically during strenuous lifting tasks. Static isometrics have been a valuable training option for the low back for over 60 years (Mueller , Rohmert W. Die Geschwindigkeit der Muskelkraft zunahme bei Isometrisches Training. Int Z Agnew Physiol. 19:403-419. 1963). A more recent meta-analysis reached the conclusion that isometric lumbar spine training was safe and effective for chronic low back pain (Sutanto, Effects of Different Trunk Training Methods for Chronic Low Back Pain: A Meta-Analysis, Int J Environ Res Public Health, 2022 Mar). For this reason and to avoid injury during training, there are compelling reasons to use isometric training, especially when applying supramaximal resistance. There are three protocols for applying isometric force to the spine.

The classic isometric exercise is to have the target muscle contract maximally against an immovable object. The internal tension of the muscle reaches a high level and there is no change in muscle length. This has been referred to as "pushing isometrics" (Oranchuk DJ, Scientific Basis for Eccentric Quasi-Isometric Resistance Training: A Narrative Review, J Strength Cond Res, 2019 Oct). In pushing isometrics the predominant force production is concentric muscle force. The problem with pushing isometrics is that the level of force is determined by the effort of the patient and is difficult to control or replicate. Also, the level of force comes solely from concentric capacity of the muscle, which does not have an overload stimulus for strengthening. However, there are additional scenarios where the muscle exerts effort against movable resistance arm. The client exerts force against the movement arm and holds the weight at a certain spot in the range of motion for some predetermined period of time. The starting weight should be between 70% and 80% of the 1RM. As fatigue sets in there is more and more difficulty in holding the weight in place and eventually the muscle eccentrically lengthens. After the client can maintain a certain weight at a certain point in the range of motion for a predetermined period of time, the weight can be increased. This style of isometrics is call "yielding isometrics".

Yielding isometrics have been described as follows: **"**researchers have demonstrated that "yielding" (resisting an external force) isometrics, with the intent of preventing eccentric muscle action, creates different fatigue and neuromuscular characteristics compared with "pushing" (exerting force against an immovable object) isometrics" (Oranchuk DJ, Scientific Basis for Eccentric Quasi-Isometric Resistance Training: A Narrative Review, J Strength Cond Res, 2019 Oct). In "yielding isometrics" a heavy but submaximal weight is applied with the muscle shortened and the trainee is instructed to hold the weight in place. Inevitably as fatigue develops the weight gradually forces the muscle to lengthen and eccentric muscle force is engaged. Because some eccentric lengthening occurs, this has been termed "Quasi-isometrics". The advantage of yielding isometrics is that a known amount weight can be applied and the time under tension can be measured. This allows the principles of progressive resistance exercise to be applied. Training can begin with a light resistance and the amount of time and effort to hold the weight can be assessed. If the weight can be held for a full 30 seconds, the resistance can be increased for the next training session.

The final level of "quasi-isometric" resistance is based on the force-velocity curve. With a progressive increase in the amount of resistance applied, the muscle will eventually be loaded with a weight that is at or above its maximal concentric force level and it becomes supramaximal. It has been shown that when loads are at low supramaximal muscle force levels, no higher than 20-30% above 1RM, the lengthening velocity of the muscle is very slow and effectively zero (Suchomel, T., et al. Sports Medicine, 2018). In practical use, these minimal velocities at supramaximal loads have been described as "elastic creep" (see graph below). The value of supramaximal yielding isometrics is that it represents the forces the lumbar extensor muscles see in "real world" strenuous lifting conditions. Because the lumbar extensors are architecturally designed to withstand supramaximal eccentric loads, it stands to reason that they should be trained under these conditions.



It should be structured to begin supramaximal training at a submaximal level and through the process of progressive resistance increase the amount of weight up to and above the supramaximal level.

Progressive Yielding Isometrics on Selectorized Equipment

One ‘low tech’ method of applying a known amount of eccentric force to the lumbar spinal erectors is to eliminate the concentric raising of the weight. The selectorized weight stack can be set at level that represents a moderate perceived effort, 5-6 out of 10. The therapist or trainer then could manually assist the patient in raising the weight until the user is in the neutral or extended position. Alternatively, the patient could push with their arms against their thighs to raise the movement arm up to the upright position. The patient can then hold the weight stack in upright or extended position for some duration of time. Clinical usage as shown that about 30 seconds seems to be length of time to maintain this static posture. This “yielding” isometric technique can be done under a known amount of load that can be incrementally increased once the time target is reached. With progressive resistance, the patient will eventually advance to loads with isometric holding that exceed the concentric 1RM. At this point the lumbar muscles will have improved capacity for work with a reduced chance of injury.

Progressive Yielding Isometrics with Motorized Assistance

The yielding isometric program can be accomplished with motorized assistance which can minimize spinal loading in the flexed posture. A warm up set of conventional six to ten repetitions at about half of the training weight is advised before static training. To begin the exercise, the training weight is selected and the movement arm is set to approximately 20 to 30 degrees of flexion. The trainer starts by entering the amount of weight that the patient will be using eccentrically. The computerized motor is preprogrammed to provide 25% assistance of the eccentric weight to assist the patient while raising the weight. The patient raises this lighter resistance to the upright, neutral position where the motor is triggered to release the assistance and the patient is under the full eccentric training weight. The patient is instructed to hold the weight in place for 30 seconds. At the point where the patient cannot hold the weight upright and the weight begins to descend, the motor will be signaled to again provide the 25% assistance and the patient lowers the weight down to the starting position. Similarly, if the patient holds the static weight for the full 30 seconds, the motor is again signaled to provide assistance so the weight can be safely lowered to the partially flexed starting position. If the patient is able to hold the static weight for the full 30 seconds in two consecutive training sessions, the weight can be incrementally increased. Even as the eccentric weight is increased, there will always be a 25% difference between the heavier eccentric weight and lighter weight in the flexed starting position.

Isotonic Enhanced Eccentric with Motor Controlled Assistance

When concentric based training has stalled, there are advantages in training the lumbar extensors with both eccentric and concentric movements since they each have different adaptations to exercise. There are two caveats in using enhanced eccentric resistance applied in full spinal flexion. Because the lumbar spine motion resembles a bending post, there are higher, dangerous tension forces on the spine itself in the flexed position as opposed to the upright position. To compound this problem, the stability offered by muscular force is more effective in the neutral, upright spine than the flexed posture. This is due to the more favorable angle of muscle pull on the neutral spine. For this reason, full range of motion training carries the real risk that a load that is appropriate in the neutral range of motion may actually be harmful in excessive flexion. This is avoided with motorized assistance by reducing the resistance as the patient flexes forward. During an eccentric loading it is important to use less forward flexion under supramaximal eccentric resistance.

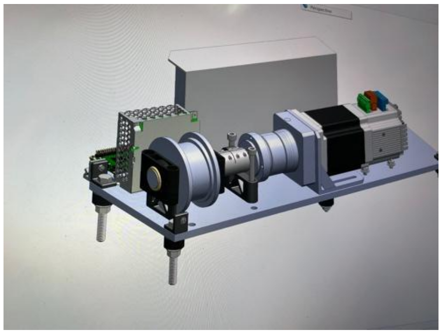
With motorized assistance, it is recommended to perform the concentric stroke with a lighter weight and then, once in the upright extended position, transition the weight to the heavier eccentric resistance. For healthy adults, the safest range of motion to support an enhanced eccentric resistance would be from the extended positon to only 30 degrees of lumbar flexion. This means that after lowering the eccentric weight to about 30 degrees of flexion, the resistance would transition back to the lighter concentric weight. The patient would then raise the lighter concentric weight back to the extended position. Upon reaching the extended position, the heavier eccentric resistance would again be applied and the cycle repeated. In this protocol upon reaching the desired number of repetitions, the eccentric weight would be raised approximately 10% and the concentric would be proportionately increased as well.

General Comments on Eccentric Resistance Training Systems

The Technology

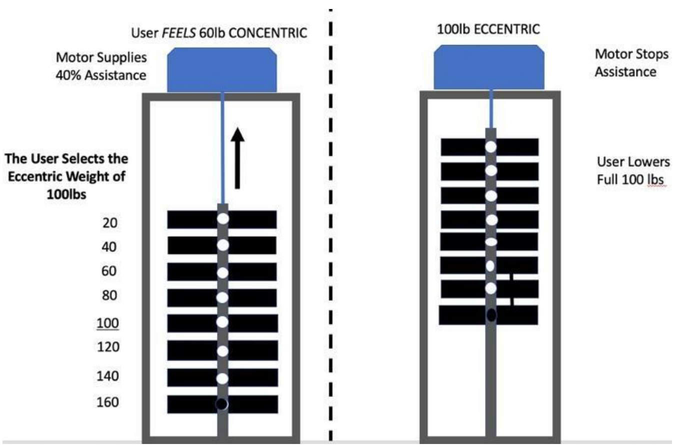
There have been innumerable attempts create eccentric abled resistance systems. There are systems that use motorized *resistance* which has an unfamiliar "feel" and offer a limited number of exercise movements. Others use an "eccentric only" strategy that disrupts the normal lifting motion. The ideal solution is to augment existing selectorized equipment and free weights with the eccentric enabling technology. Presently, the most logical mechanism for providing eccentric overload training is to employ motorized *assistance*. For example, if you are designing a system in which 250 pounds are raised and 300 pounds are lowered, you don't want to have to manipulate a full 250 pounds and certainly not the heavier 300 pounds. The most efficient way to accomplish this is to just manipulate the difference between the two, 50 pounds. Thus, the most efficient (and safest) system is to provide a precise amount of assistance to the user while the weight is being lifted and then when the weight is lowering remove the assistance.

To split the repetition into its two phases, the motor must constantly track and respond to the movements of the client. This is called "Human-Computer Interaction" which is a field that focuses on optimizing how users and computers interact using sensors detect human activity and responding with a specific intervention. For an eccentric based system to operate it must track and analyze the wide variety of movement variables and respond accordingly. Specifically, for eccentrics the system must track: 1) How much weight the user is lifting; 2) The speed at which the weight is moving; 3) The direction in which the weight is travelling; and 4) When the desired goals of exercise have been met.



Computer-Controlled, Motorized Assistance System

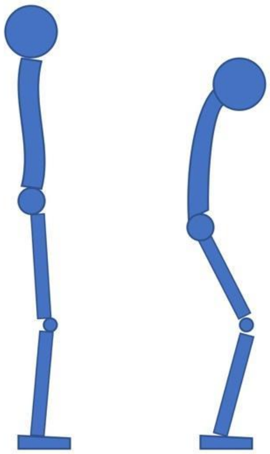
In addition to these requirements, the system needs to react quickly and smoothly in order to make its interactions seamless the user. These timely interactions are critical and occur at the transitions between concentric and eccentric strokes. For example, imagine a user who is doing an arm curl where 60 pounds is raised concentrically and 100 pounds is lowered eccentrically. The user would raise the 60 pounds and upon reaching the top of the repetition would be ready to receive the heavier eccentric resistance. Waiting for even one half of a second before lowering the weight would be a significant disruption of the normal lifting motion. In addition, the transition of applying an extra 40 pounds of resistance must be carefully controlled. The added weight must be gradually applied over a short period of time to create as normal a transition as possible. Also, the transition at the bottom of the repetition must also be timely and smooth as well. When the user is lowering a supramaximal weight and reaches bottom, the assistance must be rapidly provided for a smooth transition back to the concentric phase. Thus, a successful system for allowing enhanced eccentric training must closely monitor and react to real-time human movement.



Eccentric Lumbar Training- The Gateway Exercise

As was stated, the critical muscles which are more likely to lose strength from disuse, aging, height loss, and possible injury are the lumbar extensor muscles. Submaximal isometric training is a well-tolerated, effective technique to address these important muscles and through progressive resistance, restore their function. If this was the only resistance exercise that elderly patients did, there would be significant benefits in function, posture, and pain relief. However, there are additional exercises that if done in conjunction with lumbar strengthening that can provide even further benefits. As stated, in addition to the lumbar extensors the muscles that maintain upright posture include the knee extensors and the hip extensors. Collectively they are also referred to as the “Posterior Chain”.

Similarly, the upright posture is sometimes referred to as the “Spinopelvic Axis”. There are numerous ways to assess how bent forward a patient is, but generally it is an assessment of how well centered the head is over the pelvis. As lordosis is lost in the lumbar spine, the patient compensates by bending the hips and knees. Though the weakness in the lumbar spine may be the source of the problem, the hip and knee extensors are also involved.



Although the barbell squat can address the whole posterior chain, it is almost universally done by young, healthy athletes. Unfortunately, this movement is highly technical, difficult to perform, and uncomfortable for most of the general population. However, in addition to isolated lumbar extensor training there are two other exercises that can done to replicate the benefits of the barbell squat, with little of the physical discomfort.

Once the patient has developed sufficient lumbar extensor strength, another key movement is the parallel grip deadlift, also known as the trap bar deadlift. Because the arms are suspending the weight at the side of the body instead of in front of it, there is less bending force on the low back. In addition, the height of the handles can be adjusted to a level to which the lifter can bend. While the lumbar extensor muscles focus on the lower back, the parallel grip deadlift applies force to virtually the whole of the axial musculoskeletal system. This movement provides a widespread stimulus to include loading the thoracic spine. For the purposes of improving bone density, this exercise can address the critical thoracic spine as well as the lumbar spine. Leg strength is involved by the having the patient begin in the crouched position.

Although the gluteal and quadriceps muscles are involved in a dead lift movement, they can be more directly addressed by a lower extremity movement. The seated leg press is very accessible to the general population, as well as the elderly, so it has potential widespread application. The benefit is that because the weight is not held in the hands or on the shoulders, the user can tolerate higher, more appropriate resistance for these muscles. Strengthening with the leg press addresses the important hip and knee movements, not only increasing their capacity for function but also providing protection from falling and developing osteoporosis.

The combination of these three exercises as an essential focus for elderly resistance training led to the development of a single machine on which all three can be performed. Coined the “BMD” unit (for Bone Mineral Density) the consolidation of these three exercises into one machine is the most cost effective way of providing these movements with eccentric resistance.

Three Essential Movements of the Spinopelvic Axis Performed on the Lumbar Extensor Frame

The hip extensors and knee extensors are not as eccentrically structured as the lumbar extensor muscles. However, there are still important reasons why these muscles should be trained with enhanced eccentric overloads. One major, practical reason is that eccentric training needs to be done less frequently so clients will only need once-a-week training. This lower requirement increases adherence to a long-term program. A more important reason is that, as seen in the physiology section, during eccentric tensioning the mechanical force reaches a level that is sufficient to stimulate adaptation in the involved tendons and the skeleton.

Summary

1) **The lumbar extensor muscles eccentrically function to stabilize the lumbar spine.**
2) **Aging, disuse, injury, and loss of disc height weakens the lumbar muscles**
3) **Lumbar weakness can lead to loss of spinal alignment, back pain, and osteoporosis**
4) **Inability to stand upright is largest source of disability in the elderly**
5) **Prevention requires long term resistance training beginning in the 5th decade.**
6) **Isolated training of the lumbar muscles is the single most important intervention**
7) **Begin with conventional, concentric resistance until progression plateaus**
8) **Then increase the stimulus with enhanced eccentrics to gain further progress**
9) **Eccentrics decrease time, effort, and frequency which promotes adherence**
10) **Add hip, and knee movements when lumbar strength is restored**