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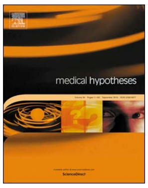

Biotensegrity and myofascial chains: A global approach to an integrated kinetic chain

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ABSTRACT

Human movement is a complex orchestration of events involving many different body systems. Understanding how these systems interact during musculoskeletal movements can directly inform a variety of research fields including: injury etiology, injury prevention and therapeutic exercise prescription. Traditionally scientists have examined human movement through a reductionist lens whereby movements are broken down and observed in isolation. The process of reductionism fails to capture the interconnected complexities and the dynamic interactions found within complex systems such as human movement. An emerging idea is that human movement may be better understood using a holistic philosophy. In this regard, the properties of a given system cannot be determined or explained by its components alone, rather, it is the complexity of the system as a whole, that determines how the individual component parts behave. This paper hypothesizes that human movement can be better understood through holism; and provides available observational evidence in musculoskeletal science, which help to frame human movement as a globally interconnected complex system. Central to this, is biotensegrity, a concept where the bones of the skeletal system are postulated to be held together by the resting muscle tone of numerous viscoelastic muscular chains in a tension dependent manner. The design of a biotensegrity system suggests that when human movement occurs, the entire musculoskeletal system constantly adjusts during this movement causing global patterns to occur. This idea further supported by recent anatomical evidence suggesting that the muscles of the human body can no longer by viewed as independent anatomical structures that simply connect one bone to another bone. Rather, the body consists of numerous muscles connected in series, and end to end, which span the entire musculoskeletal system, creating long polyarticular viscoelastic myofascial muscle chains. Although theoretical, the concept of the human body being connected by these muscular chains, within a biotensegrity design, could be a potential underpinning theory for analyzing human movement in a more holistic manner. Indeed, preliminary research has now used the concept of myofascial pathways to enhance musculoskeletal examination, and provides a vivid example of how range of motion at a peripheral joint, is dependent upon the positioning of the entire body, offering supportive evidence that the body's kinetic chain is globally interconnected. Theoretical models that introduce a complex systems approach should be welcomed by the movement science field in an attempt to help explain clinical questions that have been resistant to a linear model.

Introduction & background

Aristotle, in his *Metaphysica*, was believed to have said, "the whole is greater than the sum of its parts", an ancient phrase that has come to represent the philosophical position of holism. The central tenet is that the properties of a given system cannot be determined or explained by its components alone, rather it is the complexity of the system as a whole, that determines how the individual parts behave [1,2]. The opposing view, reductionism, prefers to break the whole into its isolated parts, attempting to simplify the process to more fully understand the whole [1,3]. The "parts versus whole" debate has led to some divisions amongst clinicians, scientists and researchers. In human movement science, the preferred philosophical approach is often one of reductionism. As such, most movement patterns, regardless of their complexity, are analyzed through a linear framework of isolated muscle groups, based on singular muscle attachments and isolated joint actions.

Within the field of human movement science, notable movement

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Fig. 1. Dynamic Knee Valgus: "medial collapse" of the lower limb. (1) contralateral pelvic drop, (2) femoral internal rotation, (3) knee valgus, (4) tibia internal rotation, and (5) foot pronation.

dysfunctions exist that may benefit from both a whole and parts perspective. One such dysfunction is dynamic knee valgus. Dynamic knee valgus is generally regarded as an aberrant biomechanical pattern, occurring across three planes of movement consisting of internal rotation and adduction of the femur and concomitant contralateral pelvic drop (Fig. 1). The combination of these faulty movements leads to an uncontrolled medial displacement of the knee which contributes to common lower extremity injuries such as patellofemoral pain syndrome and anterior cruciate ligament injuries [4–7]. In a bid to simplify the complexity of human movement, many scientists and clinicians rely on a reductionist framework to analyze and correct aberrant patterns such as dynamic knee valgus [1,3]. Consequently, a common supposition is that re-education of knee mechanics and lower extremity alignment [6,7] can be achieved through one or all of following mechanisms 1) local-specific strengthening (e.g. knee) 2) co-contraction exercises (e.g. quadriceps/hamstrings) and 3) targeting impairments in regions immediately proximal to the knee (e.g. hip). However, there is ongoing debate whether stabilization of the lower extremity and pelvis can be addressed in such a simple linear manner, and if increasing individual muscular strength at a specific joint carries over to measurable biomechanical outcomes during complex functional movements [8–10].

In a highly complicated human movement such as running there are multiple parts of many different human systems interacting simultaneously. Attempting to disentangle the interactions of these complex systems with a reductionist paradigm may overlook the complexity of the human system and limit our understanding. Our paper proposes that in order to effectively alter movement kinematics and forces during high-speed movements, there must be an advancement in clinical reasoning. We also propose that implementation of a more holistic framework, based on nonlinear or dynamic complex systems theory [11–13], will enhance our understanding of the neuromusculoskeletal system, foster creativity in rehabilitation prescription and ultimately improve clinical outcomes.

Muscle synergies

Synergy is derived from the Greek word synergos, meaning "to work together." The concept of synergy is an aspect of the parts vs. whole debate, meaning many parts contribute to the whole, but if the parts work together in a purposeful manner, synergies can arise. Human movement is a clear illustration of the concept of muscle synergy, whereby different groups of singular muscles work together in unison to produce coordinated movements of the whole organism [14,15]. Although the existence of muscle synergies seems logical, this remains a controversial area as much of the evidence in this field has been limited to behavior observation in humans or animals, or direct stimulation of the motor system [14,15]. Consequently, there is continued debate around the mechanisms of neural control underpinning muscle synergies [16]. The most popular hypothesis is that the central nervous system accesses a flexible but small number of neurally-established functional muscle groupings. However, others have suggested that muscle synergies may even be driven through non-neural interactions such anatomical or mechanical constraints [17]. Some authors have suggested that there might be just a few specific motor patterns generated within the CNS, with individual muscles joining in to adjust to the slight variabilities of the specific task [18,19].

One method of examining muscle synergies is through the use of electromyography (EMG), which can identify the electrical activity of the individual muscles to determine if those muscles are working together to accomplish a given task as well as the EMG wavelengths in an attempt to determine the neural origins of muscle synergies [20]. In order for EMG to identify if specific muscles are working together to accomplish a task, the task being studied must be rich enough in movement variability, allowing the nervous system adequate opportunity to demonstrate various control strategies. If the task is too constrained, the nervous system will only have a limited number of ways to address the task, as a result the same muscles will appear as if they are working in synergy, but in reality, the results are secondary to poor methodological design. Flawed research methods are often the most common criticism for the concept of muscle synergies [15,21–23]. Clearly, more explanatory and pragmatic research needs to be conducted on the concept of muscle synergies to more critically evaluate the mechanisms under which they occur.

Human movement is an integrated kinetic chain

Preventing dynamic knee valgus, or limiting its associated joint forces, is an important objective in movement science research as well as in rehabilitative interventions. Many clinicians now target strength impairments in regions immediately proximal to the knee (e.g. hip). There is logic to this approach as the femur represents the primary anatomical link between the knee and hip. Furthermore, there is evidence that this approach has positive effects on pain and function in patients with patellofemoral pain [6]. However, a key limitation is that proximal hip strengthening programs fail to change biomechanical outcomes during more complex movements like running and jumping [8,10,24]. Evidence has shown that there is not a direct or linear cause and effect link between these two variables [8], most likely because the isolated strengthening approach is too simplistic to address complex movements.

Another commonly held axiom within movement and rehabilitative science is that local joint stability is the result of muscles on opposite sides of the joint contracting together otherwise referred to as co-contraction or co-activation [25]. Exercises that involve local muscular co-contraction at the knee are commonly used in research, rehabilitation and prevention strategies, with the rationale that they can help to control biomechanics in this region, particularly dynamic knee valgus. Approaching movement in this manner reflects the traditional view of the kinetic chain, which is commonly described as upper and lower quarters, or "parts" within the system. But it may be more appropriate to consider the kinetic chain as a whole or a globally interconnected system.

Hypothesis

A new paradigm has emerged that suggests long muscle chains could act similarly to organized muscle synergies, providing sensory neuromotor input and are linked together anatomically via soft tissue viscoelastic myofascial envelopment [26–28]. The idea of the musculoskeletal system functioning as interconnected muscular chains, and not numerous isolated muscular origins and insertions challenges current dogma and is sparking more debate in the "parts versus whole" dialogue within the movement science field. Our hypothesis is that these long polyarticular interconnected muscular chains, formed by individual muscles sharing common myofascial connections, could be utilized to inform movement science research as well as targeted with specific interventions to alter faulty biomechanical movements such as dynamic knee valgus. If this hypothesis is proven it would essentially change the landscape on how human movement is perceived in the fields of movement science research and rehabilitative interventions.

Evaluating the hypothesis

Tensegrity & myofascial force transmission

The term tensegrity was coined by Fuller in 1962 and was a portmanteau of tension and integrity [29]. Tensegrity principles have been used extensively throughout the cellular biology literature to help explain cell structure, shape and mechanical stability [30]; we are suggesting these same principles are applicable to human structure and movement. The concept of tensegrity can be used to describe how the human kinetic chain is globally connected [28,31]. Tensegrity postulates that pre-stressed tensegrity structures are formed from a series of compression resistant elements (the bony skeletal system) that have no rigid connections from element to element but are held together within a web of continuous viscoelastic tension elements (the musculotendinous system). It is clear the body can be viewed as a large tensegrity system, as the bones have no rigid connections amongst one another, but are supported by viscoelastic musculotendinous elements that provide constant elastic tension within the system, even at rest [31–33]. Later, the term biotensegity was adapted by Levin who hypothesized that pre-stressed tensional integrity could be the mechanism by which the body creates stability within different systems and organs, particularly the spine [32,34,35]. It has been proposed that the resting muscle tone throughout the musculoskeletal system provides compression and tension between the bones, giving the body the ability to be upright and mobile [32,34]. When load is applied to the human biotensegrity system, as during initial loading response, and the musculoskeletal system needs to become more rigid, the interconnected muscular chains can contract, allowing stress and load to be applied to the body [32]. The integrated kinetic chain concept would insist that these muscular pathways be joined between one another, providing a large interconnected network of polyarticular muscular myofascial chains which have the ability to transfer force amongst one another.

There is evidence to support the concept of myofascial force transmission both through cadaveric research [26,36,37] and in vivo studies [38–42]. Cadaveric research in this field usually involves placing specific muscles under traction, allowing for direct observation of myofascial force transmission. Two cadaveric models have already shown evidence of myofascial force transmission between the lumbodorsal fascia and the contralateral gluteus maximus [36,37]. Carvalhais et al. [39] have reported similar patterns in vivo; using EMG to confirm the relaxed state of hip musculature during testing, they confirmed that tensioning the lumbodorsal fascia, in the direction of the contralateral gluteus maximus, resulted in a direct change to passive torque of the hip.

The evidence of myofascial force transmission strengthens our hypothesis that these interconnected muscular chains would have the ability to transmit forces via connective tissue envelopments to surrounding structures and not solely through tendinous attachments between muscles [41,43,44]. The view of the human body being one interconnected muscular system contradicts current biomechanical testing models. Current models test the muscular system by isolating muscle groups, utilizing a reductionist methodology. Although a reductionist approach simplifies clinical research and intervention, it does not reflect the complex, multifaceted and nonlinear nature of human movement.

There has been growing evidence to support the idea of biotensegity and humans as tension dependent organisms [27,31,32,45,46]. A recent systematic review found strong evidence supporting the anatomical existence of several muscular myofascial chains [27]. One chain of particular clinical interest, the back functional line [26] (Fig. 2), which comprises a myofascial connection between the latissimus dorsi and the contralateral gluteus maximus via the thoracolumbar fascia [27], which clinicians commonly refer to as the "posterior chain". There is further evidence that passive myofascial connections exist between the gluteus maximus and its distal attachment to the iliotibial band [26,39,47] and into the fibularis longus muscle of the lower leg [48]. There is also evidence that utilizing myofascial chains and interconnected connective tissues, that are remote from the targeted tissues during the intervention demonstrate altered effects in both strength and range of motion [49–52]. Although preliminary, the entirety of this evidence supports our hypothesis that integrated muscular myofascial connections, can make important contributions to the stability of the human skeleton [31,36,38,39,49,53–55].

It is critical to understand that the idea of a globally integrated dynamic kinetic chain would include many of these muscular chains in series throughout the human body, and as in any complex system, these muscular chains are in constant interplay amongst one another. A recent systematic review [27] that examined the work by Myers [26] supports the existence of 5 proposed myofascial chains with moderate to strong evidence. The back functional line (Fig. 2), although highlighted here because of its common clinical usage and familiarity amongst clinicians, is not the only muscular myofascial chain supported with evidence. There is now evidence supporting multiple myofascial muscular chains coursing throughout the body [27], synergizing their efforts to provide three-dimensional human movement while constantly attempting to balance stability and mobility. These muscular chains often have an opposing chain to help achieve this balance within the musculoskeletal system. As an example, the back functional line pairs with an "anterior chain" termed the front functional line (Fig. 3) (which runs from the pectoral insertion on the humerus to the insertion of the adductor group on the contralateral femur), which is also supported by strong evidence [27]. Given the recent evidence supporting these polyarticular muscle chains, we propose our hypothesis as a clinical paradigm shift that suggests intermuscular myofascial connections, such as the back functional line (Fig. 2), the front functional line (Fig. 3) and others, can impact force transmission and stability to the entire lower extremity, and quite possibly even control faulty movement patterns such as dynamic valgus at the knee joint [31,36,38,39,48,53,56].

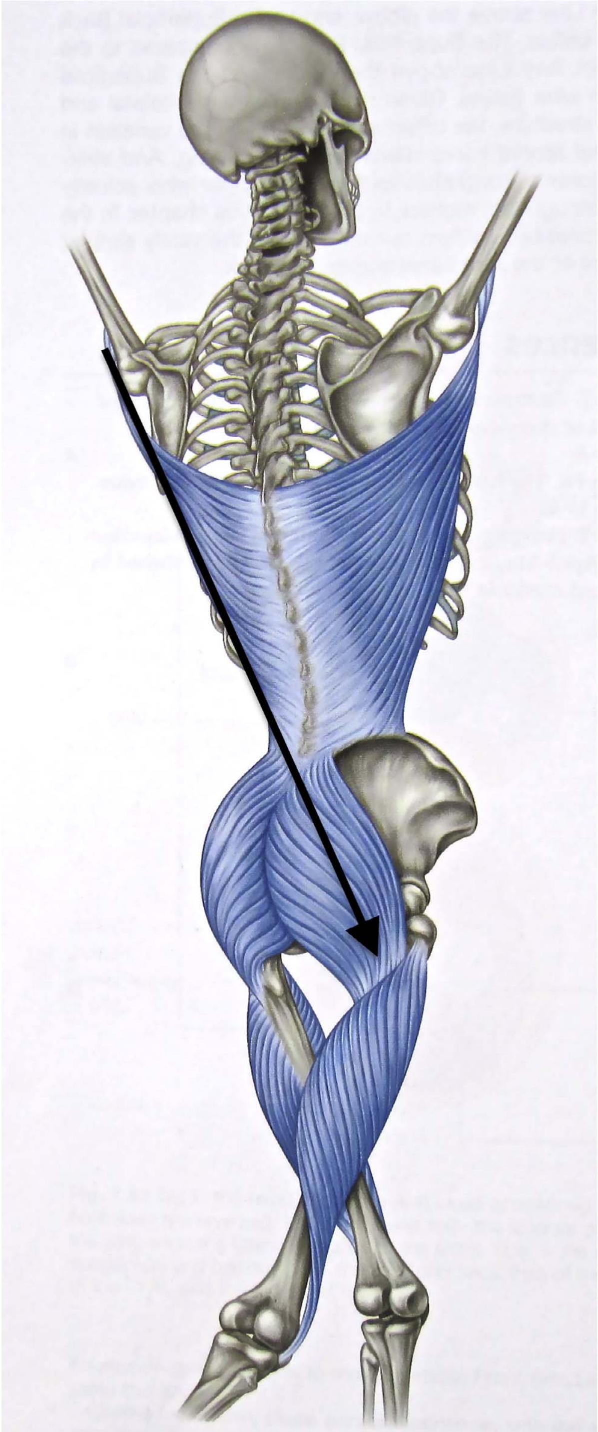

Fig. 2. Illustration of the back functional line as described by Myers. Reprinted with permission: [26].

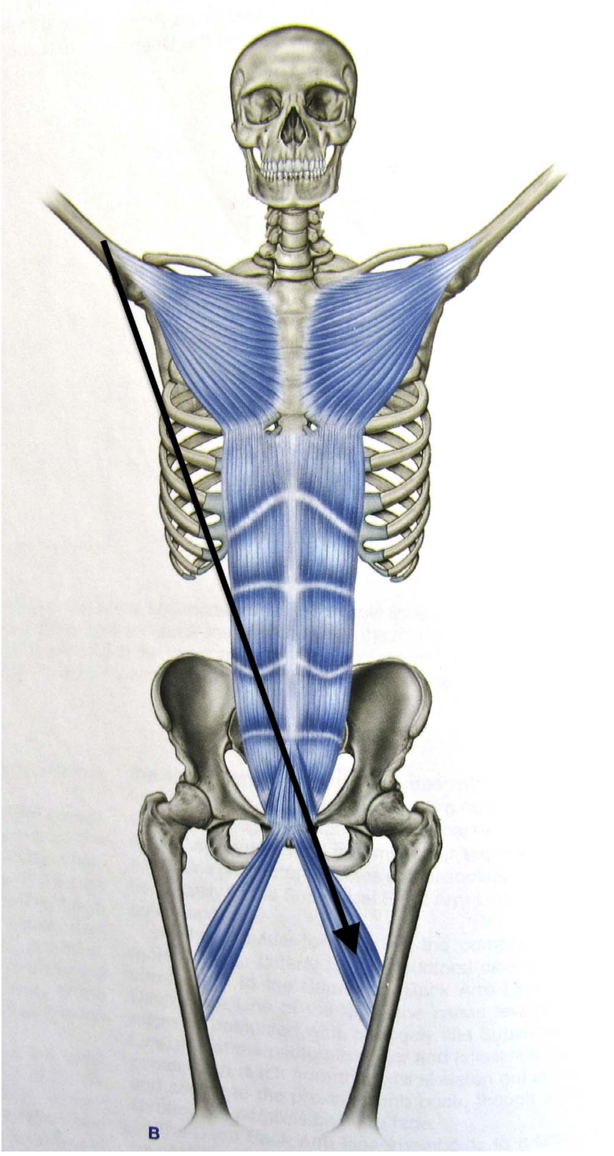

Fig. 3. Illustration of the front functional line as described by Myers. Reprinted with permission: [26].

Testing the hypothesis

In an effort to support our hypothesis, we refer to the work of Tak and Langhout [57], who have used key myofascial pathway concepts to provide a vivid example of how ROM measures at one joint are dependent upon the positioning of the entire body. In their example, hip rotational range of motion is altered when accompanied by full trunk counter-rotation and end range hip extension, a position that uses myofascial planes to eliminate slack in the musculoskeletal system. Tak and Langhout's novel approach to measuring hip rotation with concomitant trunk counter-rotation illustrates how the back functional line connects the ipsilateral gluteus maximus on the lower extremity to the opposite upper extremity latissimus dorsi via the dorsal thoracolumbar fascia and how this might limit ROM secondary to its vast integration of connective tissues. Adding trunk counter rotation (as movement about the vertical Z axis) is potentially analogous to wringing out a wet towel, as the rotation increases toward end range so does the tension within the entire musculoskeletal system. The trunk has been implicated as a crucial variable in other movement based research, such as injury prediction [58], and thus, it is reasonable to suggest that coordinated trunk movement and its reciprocal interaction with the pelvis sit as a central tenet of our paradigm.

Another recent study, informed by myofascial chain concepts, has demonstrated that hip and trunk strengthening can lessen femoral adduction, a component of dynamic knee valgus, noted during a step-down task [56]. Even though strengthening the hip and trunk has demonstrated biomechanical changes at the knee during a step-down task, the question remains if interventions can be developed that will alter biomechanics at faster and more complex tasks such as running. Current hip focused interventions have been unable to alter biomechanical changes at these higher demand sporting activities [8,59,60] but creating new interventions with a myofascial chain approach could possibly alter these higher speed tasks. Identifying the methods by which these myofascial chains are integrated into an intervention design is the task of future research and is the underpinning ideology behind our hypothesis.

Rehabilitative & movement therapy: clinical implications

Adopting a more holistic approach to the musculoskeletal system could have far reaching applications into many different branches of movement science, particularly those relating to rehabilitation and exercise prescription. For example, the existence of viscoelastic myofascial muscular chains working within a biotensegrity model, suggests that exercises must be tailored to maximally challenge eccentric function, multi-joint stability, elastic energy storage, and end ranges of motion [54]. The corollary could be the development of elongated viscoelastic myofascial muscle chains which would not only provide increased eccentric control at end ranges of joint motion, but would also provide a great deal of passive tension and stability within the global musculoskeletal system. In line with our hypothesis, future research is required to delineate the most appropriate movements to facilitate myofascial force transmissions relevant to dynamic lower extremity alignment, mobility and stability.

A complex systems theory would suggest there are additional systems operating with the ability to alter movement patterns, so as not to rely on a singular linear model [13]. We must acknowledge that neuromuscular and sensorimotor control is part of this extremely complex process occurring between multiple dynamic systems, which is effectively described in the Grand Unified Theory of human performance [61]. The body is manipulating infinite variables, in a nonlinear fashion to execute movements efficiently, in an effort to be as economical as possible with the body's resources. One example of a system that is always engaged during human movement is the sensorimotor system, which is constantly having to work simultaneously with other systems. The sensorimotor system is the processing mechanism for the central nervous system which allows the brain to receive information from the environment creating both feed-forward [62,63] and feedback loops [12,13,64]. Literature has supported the idea that neuromuscular and sensorimotor control is potentially more important than individualized muscle strength to control movement [8,65–67]. That said, it is quite possible that when muscle chains are trained in series (not in parallel as agonist/antagonist co-contractors) these highly rich proprioceptive and sensory dense muscle chains [54] can have a profound impact on movement. It is likely that mastery of human movement involves a higher level of motor learning, and the utilization of the global network of interconnected muscular chains, which are potentially expansive networks of immense sensory organs [68], may expedite the motor learning process ultimately enhancing task specific neuromotor control.

Discussion & implications for future research

Our proposed framework is underpinned by a global mechanism of functional stability and we have outlined the potential clinical utility of moving beyond a linear model and to adopting a more holistic approach. Research should continue to identify and understand the mechanistic relationship between optimized biomechanics during human movement and globally targeted intervention strategies utilizing myofascial muscular chains. Currently, there are no studies that examine the potential impact on lower extremity alignment or dynamic knee valgus while utilizing the myofascial muscular chains and their sensorimotor effects to facilitate the functional components needed for eccentric control of lower extremity and efficient human movement of the global human organism. Interestingly, a recent systematic review reported "that most skeletal muscles of the human body are directly linked by connective tissue and examining the functional relevance of these myofascial chains is the most urgent task of future research [27]."

Patellofemoral pain syndrome and anterior cruciate ligament injuries have similar mechanistic biomechanical origins, and although there has been extensive research and development of anterior cruciate ligament injury prevention programs, few sports are reporting subsequent reductions in injury incidence [69–71]. Therefore, it is important that future studies within the realm of rehabilitative science develop and implement exercise programs that are informed by this contemporary framework. For example, more research is needed on the vast myofascial and tendinous connections of the gluteus maximus, which bridge the upper and lower extremities and have potential to control multiplanar movements.

Conclusion

Theoretical models that introduce a complex systems approach should be welcomed by the movement science field in an attempt to help explain clinical questions that have been resistant to a linear model. A change in mindset could create a paradigm shift that allows the clinician or researcher to consider the multifactorial nature of complex systems and identify patterns that are occurring on a more global scale within the dynamic system itself. It is important to recognize that even the most recent systematic review indicates that biomechanical mechanisms explaining the therapeutic effects of proximal strengthening exercise remain unclear [72]. Worth considering is that the therapeutic effects of proximal strengthening cannot be explained by a simple, linear approach and may require a more dynamic, complex systems approach as we continue to try to understand, "potential mechanisms underpinning treatment effects [73]." In accordance with this effort, a holistic systems-based framework has been offered to help conceptualize that human movements are based on a globally interconnected musculoskeletal kinetic chain.

The concepts offered here use core anatomical and biomechanical principles to introduce a hypothetical new paradigm for neuromotor control and dynamic stability of the human body. Its central tenet is that the musculoskeletal system comprises a network of polyarticular muscle chains working within a biotensegrity model. These intricate and system-wide muscular chains may be able to help apply a complex systems approach to research in the attempt to better understand the interacting variables involved in human movement, particularly with regard to higher level functional activities. It is anticipated that the new paradigm offered here can provide an innovative lens through which investigation of future research can be conducted with the hope of informing evolved evidence-based interventions. These hypothesized interventions could be the missing elements needed to optimize current rehabilitative programs to demonstrate measurable decreases in injury incidence as well as impact potential biomechanical changes within the movement science field where current programs have failed to demonstrate success.

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Conflict of interest

The authors of this manuscript declare that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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