

Integrating mental imagery and fascial tissue: A conceptualization for research into movement and cognition



Amit Abraham ^{a,b,*}, Eric Franklin ^c, Carla Stecco ^d, Robert Schleip ^{e,f,g}

^a Department of Kinesiology, College of Education, The University of Georgia, Athens, GA, USA. 330 River Road, Athens, 30602, GA, USA

^b Department of Medicine, Division of General Medicine and Geriatrics, Emory University School of Medicine, Atlanta, GA, USA

^c The International Institute for Franklin Method, Hitnauerstrasse 40 CH-8623 Wetzikon, Zurich, Switzerland

^d Department of Neurosciences, Institute of Human Anatomy, University of Padova, Via Giustiniani, 5 - 35128, Padova, Italy

^e Department of Sport and Health Sciences, Technical University of Munich, Germany. Georg-Brauchle-Ring 60/62, 80802, Muenchen, Germany

^f Department of Sports Medicine and Health Promotion, Friedrich Schiller University Jena, Jena, Germany

^g Fascia Research Group, Ulm University, Experimental Anesthesiology, Ulm, Germany

ARTICLE INFO

Keywords:

Body schema
Cognition
Dynamic neuro-cognitive imagery
Fascia
Mental imagery
Movement

ABSTRACT

Mental imagery (MI) research has mainly focused to date on mechanisms of effect and performance gains associated with muscle and neural tissues. MI's potential to affect fascia has rarely been considered. This paper conceptualizes ways in which MI might mutually interact with fascial tissue to support performance and cognitive functions. Such ways acknowledge, among others, MI's positive effect on proprioception, body schema, and pain. Drawing on cellular, physiological, and functional similarities and associations between muscle and fascial tissues, we propose that MI has the potential to affect and be affected by fascial tissue. We suggest that fascia-targeted MI (fascial mental imagery; FMI) can therefore be a useful approach for scientific as well as clinical purposes. We use the example of fascial dynamic neuro-cognitive imagery (FDNI) as a codified FMI method available for scientific and therapeutic explorations into rehabilitation and prevention of fascia-related disabling conditions.

1. Introduction

Human motor performance is a complex phenomenon involving multiple autonomic and voluntary neural circuits [1,2] associated with motor, sensory, and cognitive spheres [3,4]. Mentally envisioning a motor task or a scene—a cognitive process known as mental imagery (MI)—has been shown to positively affect motor and cognitive performance and other behavioral outcomes and to elicit brain activation similar to that during physical execution. As such, MI has become a topic of growing interest for both researchers and clinicians. To date, research on MI's role in human performance has primarily focused on its effects on muscle tissue. Because accumulating evidence points to the key role of fascial tissue in movement and its associated impediments and pathologies [5–14], including those within muscles, we propose to broaden the scope of MI's scientific research and clinical applications to include aspects of fascia, including potential neuro-cognitive ones. We therefore consider novel ways in which MI could further impact human

movement and rehabilitation by examining the role MI might have in affecting fascial tissue through motor, sensory, and cognitive spheres, and vice versa.

Increasing evidence points to links between movement and cognition [15,16] and to potential beneficial effects of incorporating self-active and cognitive components, such as MI, into movement, therapy, and rehabilitation [17,18]. Given the key role of fascial tissue in movement and its associated impediments and pathologies [5–14], we present here a science-based conceptualization of how MI could contribute to both motor (i.e., movement) and sensory-cognitive (i.e., proprioception, pain, and body schema) elements related to fascia, as well as how MI could benefit from sensory information originating from fascia. As a foundation for hypothesizing these potential bi-directional links between MI and fascia, we discuss MI's documented beneficial effects and suggested physiological and psychological mechanisms of effect on muscle tissue, along with the similarities and associations between muscle and fascial tissues at cellular, physiological, and functional

* Corresponding author. Department of Kinesiology, College of Education, University of Georgia, Ramsey Center 115 River Road, Athens, 30602, GA, USA.

E-mail addresses: amit.abraham@emory.edu, amitabr@gmail.com (A. Abraham), franklinmethod@me.com (E. Franklin), carla.stecco@unipd.it (C. Stecco), robert.schleip@tum.de (R. Schleip).

levels. In this way, we offer a conceptualization that uses “top-down” and “bottom-up” neural pathways to support the hypothesized mutual association between MI and fascia. Further, we propose that performance and well-being, including as affected by body schema and pain, may be addressed through such neuro-cognitive paths, including those associated with bodywork and movement therapies [6,9,19–22]. We then propose fascial MI (FMI) as a subtype of MI that focuses on fascial tissue, and introduce a codified MI approach that specifically addresses fascial tissue–fascial dynamic neuro-cognitive imagery (FDNI)—and suggest applications for research and clinical settings.

2. Mental imagery (MI)

Mental imagery (MI) is a self-generated cognitive process of creating and using images and metaphors in the mind [18,23,24]—including envisioning motor tasks—with or without overt physical execution [25]. Imaged contents may relate to or focus on the body as a whole as well as its specific parts and tissues. The MI process uses, and even relies upon, sensory information originating from within the body [26,27]. The quantity and quality of such information may affect MI’s characteristics, such as clarity, ease, vividness, and precision. MI enables the user to focus on such internal-to-the-body contents in a conscious, well-constructed, and selective manner [28,29], through, among others, increasing awareness and drawing attentional focus (Gose & Abraham, unpublished). Although applicable to all senses, MI primarily takes two forms: visual and kinesthetic [30]. Visual MI involves mental pictures or sights associated with the task or scene [31] from either a first- or third-person perspective [32] whereas kinesthetic MI involves mental images of sensations associated with such tasks or scenes (e.g., the imaged sensation of a contracting muscle [33,34]). Imaged and physically executed motor tasks demonstrate structural (e.g., brain activity) and functional (e.g., task duration) similarities [24,35–37]. Overlapping brain areas are activated during both imaged and overt physical execution of the same movement [30,38–40], and the time required to mentally complete an imaged task is similar to that taken to physically complete the same task [41].

MI has been studied in both basic laboratory and functional real-life settings, within a variety of tasks [30], from activities of daily living [42] to endurance sports performance [43,44], and in association with various behavioral outcomes. To date, research into MI has primarily focused on muscle tissue [33,34,45–49] and has confirmed MI’s ability to address and affect various aspects of muscle tissue activation [50–53]. For example, mentally focusing on a specific muscle in a static condition elicited a modulation of electrophysiological activity within the muscle itself [54]. Further, imaged and actual muscle activations showed similar spatial [55] and temporal [56,57] physiological activation patterns. For example, imaged eccentric and concentric muscular contractions resulted in electromyography patterns similar to those appearing during such actual contractions [45]. On the other hand, muscle-related physiological responses following MI [58,59] matched the imaged contents [45,60,61]. In a study assessing electromyographic activity during MI, imaging lifting a heavier weight resulted in greater activity within the muscle than did imaging a lighter weight [62]. Also, motor-evoked potential amplitude and pattern during MI were proportional to the relative role (i.e., activation) of the muscle as detected during actual physical performance of the same motor task [63]. Other research, however, has failed to show similar results using MI [64]. Also of interest is the finding of significantly higher muscle excitation being induced by internal (i.e., first-person) when compared to external (i.e., third-person) perspectives of visual MI [62,65], although full details regarding the imaged contents were not provided.

Among the documented beneficial gains of MI for muscle tissue are increased muscle strength [50,66,67], increased isometric force production [46], increased flexibility and range-of-motion (ROM) [33,34,37,51,68–71], and reduced stretching-related discomfort [51]. The capability of MI to affect the autonomic nervous system has been also

demonstrated [72–74] over various physiological (e.g., heart rate, blood pressure, and ventilation) responses [50,60,75–77], which matched the MI contents [45,60]. Furthermore, psychological and emotional elements (e.g., anxiety, motivation, and confidence) have also been found to be associated with MI [78,79], suggesting that such affective parameters might be regulated by MI [78,79]. Such effects could also underlie the above-described effect of MI on muscle tissue. Suggested mechanisms of effect of MI on muscle tissue include physiological and psychological ones [51,53]. Physiological mechanisms include neural changes and adaptations [37,61,67] occurring at both supraspinal (e.g., primary motor cortex, pre-motor cortex, basal ganglia, cerebellum, etc.) [17,40,52,53] and spinal [52,53,80–82] levels, rather than changes at a level within the muscular tissue itself [37,50,61,66]. Examples of such neural adaptations include better organization and effect on motor units, and increased excitability of corticospinal pathways [52,53,58,83,84]. Other literature, however, suggested physiological mechanisms within the muscle itself, including (a) motor units’ additional recruitment [85] and increased levels of activation [66] and firing frequencies [31], and (b) reduced antagonist activity [50]. Proposed psychological mechanisms include enhanced motivation [86], reduced anxiety [78], and augmented levels of self-efficacy [87], information processing [51], focus of attention [37], and body schema [8].

MI can be used as a training method (e.g., motor imagery practice, dynamic neuro-cognitive imagery) in a variety of fields, from rehabilitation [18,42,69,88–90] to sports and dance [33,34,91,92], and can be applied either solely or in conjunction with physical therapy or other therapeutic or movement training approaches, with the goal of enhancing motor and non-motor aspects of performance [25]. Further, MI can be used for addressing a wide range of behavioral outcomes, from self-confidence and anxiety to motor neuron activation.

The association between MI and pain, and its management, is another relatively new research field with preliminary promising findings [93–96]. MI has been found to modulate and reduce pain [97,98], potentially through mechanisms such as expectation, placebo, and reappraisal [96]. Another fairly novel field of inquiry is the association between MI and body awareness and schema [90]. As MI has been long known as a cognitive method for focusing on the self and thus increasing self-awareness, recent literature has discussed the role of body schema in MI [99] and the potential effect of the latter on body schema [90].

3. Fascia: Definitions and concepts

Long considered inert wrapping, fascia is increasingly identified in contemporary scientific research as a system playing important roles in human movement [100–103]. A recent definition suggests that fascia is “a sheath, a sheet, or any number of other disintegrable aggregations of connective tissue that forms beneath the skin to attach, enclose, and separate muscles and other internal organs.” [9,22,101,104] Further, the term “fascial system” has referred to as “a network of interacting, interrelated, interdependent tissues forming a complex whole, all collaborating to perform a movement.”²² Fascia assists human structure and function, including force transmission, sensory functions, and wound regulation [22] through the actions of its “fibrous collagenous tissues which are part of a body wide tensional force transmission system” (from Fascia Research Congress 2012) [105]. Fascia comprises various cells with different characteristics (e.g., receptor expression) [106]: fibrocytes (i.e., fibroblasts and numerous types of myofibroblasts) [106], adipocytes, migrating white blood cells, telocytes [107], and fasciacytes [108]. In addition, fascia comprises ground substance and collagen (i.e., triple helix glycoprotein) fibers, both forming the extracellular matrix [109]. Additional physical and neural components of fascial tissue are discussed below.

3.1. The roles and functions of fascia

Fascia provides an envelope for tissues and/or organs [110,111] as it

also absorbs [112], distributes, directs [100], and transmits [113,114] mechanical forces. As such, fascia contributes to posture and movement, locomotion, joint mobility [115,116] and stability [6], muscle elasticity [117], proprioception, respiration, and continence [100–103,115,116, 118–123]. Its role in static and dynamic proprioception [8,100,124, 125] is thought to be possible through mechanical tension transmitted to the fascia through activation of muscular-tendinous expansions into it [100], which, in return, activates free nerve endings and other fascial receptors that contribute to accurate sensing of joint ROM [100]. The hypothesized sensory-proprioceptive information (or feedback) from fascia, including body contour and physical proportions [8], may support fascia's role in body schema (i.e., the mental representation of the body and its parts in space and in relation to each other, as derived from bodily information [126]), as well as in MI in general. Further, anomalies in body schema and balance, whether seen from the outside or sensed internally, have been suggested to reflect connective tissue patterns [8]. Fascia could, therefore, contribute to efficient, coordinated, and safe movement [9,112,127] through supporting correct biomechanics [14], facilitating proprioception and interoception [8,128,129], and enhancing body schema and other self-awareness related processes. Related to this, fascial stiffness (i.e., loss of elasticity and reduced stretching ability) have been linked with deficits (i.e., decreased) in proprioception [8] and chronic sympathetic activation [130].

A mutual association between fascia and emotional-psychological aspects has been also proposed [128], including fascial physical responses to emotions. Emotional spheres could be potentially shaped by elements such as habits and body image [8], and expressed through soft tissues, including fascia [128], with the latter so-called “the emotional body.”⁸ This proposed mutual relationship between fascia and emotional-psychological aspects is in addition to other associations fascia seems to have with other body tissues and cognitive components, which are discussed below.

3.2. Similarities and associations between fascial and muscle tissues

Emerging literature recognizes ways in which fascia and muscle tissues may be interacting on histological, physiological, and functional levels. Histologically, myofascia (i.e., the fascia surrounding and residing within muscles) contains motor units [131] and myofibroblast [132,133] (or myofibroblast-like [134]) cells, with the latter containing actin-myosin filaments such as those typically seen in smooth muscles [109]. These myofibroblasts exhibit with α -smooth muscle actin stress fibers [130,135] and demonstrate active contractility capability [101] following chemical [136] and mechanical [135,137] stimuli. Physiologically, the multi-layered structure of fascia plays a role in supporting and shaping organization of muscular tissue [119,138] (e.g., though architecturally encapsulating and thus defining muscle fascicles). Fascia contributes to dissipating forces within the muscle and providing pathways and mechanical support for nerves and blood and lymph vessels [112,119,139,140]. Although some literature makes a distinction between receptors within muscle and fascial tissue [141–143], the two tissues demonstrate physiological and functional similarities in responding to injury [9]. For example, fascia adapts to tensile demands [135] through active and autonomous contraction in a smooth muscle-manner [130]. Another physiological association between the two tissues includes fascia's role in setting muscle tone through activation of fascia mechanoreceptors [19]. Also, loss of muscle length (or elasticity) following immobilization has been attributed to a shortening of muscle-associated connective tissue preceding the shortening of the muscle fibers themselves [144]. From a functional perspective, the muscular insertional expansions from underlying muscles invading into fascia [124,145] contribute to maintaining fascia basal tension, stretching it, and transferring forces from the nearby muscular tissue. Further, embedded within one another, muscle and fascia work in conjunction in force production, absorption, and transmission to both synergistic and antagonist muscles [146–148] as well as in enhancing

the force produced by muscles [146].

3.3. Neural and cognitive aspects of fascia

Fascia is considered among the richest sensory organs in the human body [149] with the vast majority of sensory nerve endings in musculoskeletal tissues originating in fascia (such as in the perimysium and endomysium) [150]. Its role as a proprioceptive and nociceptive source has been investigated from anatomical and pathological perspectives [100–103,151]. Among the neural components within fascia and in close proximity to it are myelinated (e.g., Ruffini, Golgi, and Pacini type proprioceptors) and unmyelinated [149] free nerve endings [19,152, 153] associated with surrounding and interacting muscles [154] as well as adrenergic fibers controlling local blood flow [155–157]. Functioning across different layers [158], the precise locations of fascia's rich innervations [155] are yet to be determined [100,149,155].

The neural pathways and communication patterns between the fascia and the brain are not fully understood to date [153,159], with most scientific focus being on the afferent input from fascia. Research has pointed to the role fascia may play in musculoskeletal injuries [7] and pain [10,14], including in delayed onset muscle soreness [160] and central sensitization [161], through providing a nociceptive input to the dorsal horn neurons [13]. Such a nociceptive input could result from, among others, mechanical restrictions (e.g., reduced mobility) within the fascia [12,127], as was suggested to be the case in low back pain [127]. Fascia's sensitivity to noxious chemical stimuli, resulting in pain whose descriptors (i.e., burning, throbbing, and stinging) suggest an innervation by both A- and C-fiber nociceptors, has been also demonstrated [162]. Interestingly, specific verbal descriptors (e.g., “burning,” “scalding,” “cutting,” “tearing,” “stinging”) associated with fascia-related pain differed from muscle-related pain ones [163], potentially suggesting specifically targeted neural mechanisms and pathways involved in fascial pain receptors and processing. Related to this, highest levels of pain were elicited by injecting surrounding fascia when compared to injecting the muscle (anterior tibial) itself [160], potentially explained by fascia's greater innervation when compared to other musculoskeletal tissues [150]. The association between pain and fascia may be mutual, as no causality has been established to date as, for example, for alterations in fascial tissue structure that have been detected in individuals with chronic low back pain [164].

Fascia's capability to respond to various internal and external stimuli [165,166], including emotions [8], supports the value of considering its role as a sensory-proprioceptive organ. One example is the suggested increased contractile ability/behavior (i.e., stiffness) following high mechanical [135] emotional [101], or chemical [136] stimuli. Such a responsiveness, relevant for both fascia-related stimuli (e.g., pain [164]) and conditions (e.g., fibromyalgia [167]), has been associated with the passive and active-dynamic components of fascia [101,109]. The passive component refers to the internal organization and content of the fascia acted on by other-than-fascia extra-muscular tissues reacting (i.e., via force transmission) in response to mechanical stimuli (e.g., stretch or load) [168]. For example, biochemical and remodeling responses associated with fibroblasts have been suggested in response to mechanical (e.g., stretch) stimuli [109]. The active-dynamic component refers to the specific elements within intra- and inter-muscular fascia layers that actively and autonomously contract in response to various mechanical and chemical stimuli [101,135,169–172]. This active autonomous contractility within the fascia does not seem, however, to be enough by itself to cause movement of the limbs [101].

The reactivity of both passive and active components of fascia contributes to its plasticity, a key property of fascia [20,101,131] that until recent years has been somewhat controversial in the literature given its referral to fascia as a nonelastic, passive tissue. Plasticity allows for changing physical characteristics such as alterations in fluid content, increases in arterial perfusion, enhanced fascia layer sliding, modified corticospinal excitability, and contractile activity in the myofibroblast

cells [173–176]. Fascial plasticity has been found to be activated in response to various mechanical and chemical stimuli associated with movement, bodywork therapy, exercise [177], injury, activities of daily life, movement dysfunctions [161], and pregnancy [118]. Specifically, fascia's response and adaptation following movement or training has been attributed to mechano-transduction, during which morphological changes in cells are induced following applied mechanical stress [6, 178]. Such morphological changes include fibrocytes being transformed into myofibroblasts [179], thus facilitating fascial muscle-like properties [180,181]. Further, changes in innervation of fascia have been described primarily in association with pathologies [155,157]. However, the capability of the nervous system to directly regulate morphological features of the fascial system [166] and the ability to consciously affect fascial tissue through “top-down” (cognitive-to-motor) mechanisms, including those associated with MI and other cognitive training regimen, remains mainly unknown. Potentially related to that is the fact that fascia's efferent nerve endings account for more than 50% of the total nerve fibers residing in this tissue [182], although so far only associated with a sympathetic response (i.e., increasing blood flow) [20]. However, although most of the sympathetic fibers found in human thoracolumbar fascia were located around blood vessels, thus potentially serving as vasomotor fibers [183], a significant portion of sympathetic nerve endings were located outside the vicinity of blood vessels, thus begging the question as to what their function might be [182,183]. In summary, although not fully revealed to date, the wide arrays of sensory information originating from fascia may be able to provide information regarding not only interoception and pain but also to include additional cognitive processes, such as MI. Below, we outline ways in which MI might affect fascial physiology and mobility along with some preliminary suggestions of how MI might also be affected by sensory input received from fascia.

4. Linking MI with fascial tissue: From current knowledge to future research paths

The discussed-above direct and indirect links between MI and fascia indicate the possibility of fascial changes, including plasticity and remodeling, facilitated by MI. Such cellular and extra-cellular changes and adaptations [184] might include collagen changes, remodeling, increase in shear plane motion, and changes in the tendinous material and size [9,127]. If so, fascia-related conditions, including those with age, physical training [9], and disease [167], that limit motor responsiveness might also be addressed with the cognitive approach of MI. Insofar as movement intimately involves fascia, the possibility that MI could affect fascia offers interesting research and clinical considerations of novel ways to create, test, and implement neuro-cognitive approaches to motor performance management and enhancement, including motor planning and control. Although these considerations are currently at an early theoretical stage, we recommend that MI could affect fascia through several potential paths. One path MI could affect fascia is via the autonomic nervous system, given that the latter can be influenced by MI [187–189] and is embedded within fascia. Accumulating evidence points to ways in which fascial tissue is intimately connected with the autonomic nervous system [19,20,156,190,191] thereby having an autonomic component. Such a potential effect could be achieved through both direct (e.g., increasing arterial circulation to fascia through vasodilatation thus increasing fascia hydration [20,128]) and indirect (e.g., via inter-connected autonomic and somatic efferent systems [186]) paths. This could potentially result in, among others, increased fascial viscoelasticity (i.e., the dynamic combination between viscosity and elasticity, which include phenomena such as creep, stress relaxation, and stress-strain hysteresis) thus relieving or preventing ischemic pain. Such improved physiological properties of fascia could, in return, facilitate an enhanced afferent input to the brain that could be used, among others, for MI [26,27]. Noteworthy in this context is the recently demonstrated association between chronic sympathetic

activation and fascial stiffness [130]. The suggested role of fascial tissue in other pain-related neurophysiological mechanisms, such as neural sensitization [161], as well as others associated with cognition, emotions, and thoughts [8,128,192], could also link MI with fascial tissue and potentially explain its potential to affect fascia.

Related to therapies and rehabilitation, given that MI has been shown to contribute to reducing pain sensation, it may be that fascia-targeted descending inhibitory pain pathways, similar to those thought to be activated following manual therapy [193], could be specifically addressed and activated by MI in order to reduce pain sensation of fascial origin and to regulate the autonomic nervous system [193, 194]. MI's positive effect on flexibility [37,51] could be, in addition to directly affecting fascial physiology as described above, due to MI's role in decreasing motor neuron activation, thus potentially resulting in greater motor relaxation and increased flexibility of muscle and fascial tissue. Enhanced flexibility following MI could also be due to altered programming of the motor system [195]. Further, insofar as MI supports mental relaxation, it could result in enhanced fascial relaxation, mobility, and flexibility [196,197] along with decreased resistance [37].

Simultaneously, given that MI uses and is facilitated by internal sensory information [185], such as interoception and body schema, fascia, as discussed above, could serve as a source of such sensory information with a suggested role in proprioception and interoception [8, 19,20,124,128,129,186], thus impacting MI through both conscious or subconscious mechanisms. Specifically, such an enhanced afferent information from fascia could positively affect the spectrum, clarity, precision, and vividness of the fascia-related mental contents.

In sum, we propose that MI has the potential to affect and be affected by fascial tissue in a designated manner through various channels, including modulating both the autonomic nervous system and cognitive-psychological elements such as body schema and pain. Moving forward, we suggest the value of focusing on the possibilities that 1) MI characteristics (e.g., ease, clarity, vividness) could benefit from afferent sensory information originating from fascial tissue with the purpose of improving mobility, body schema, and interoception, and 2) MI could facilitate neuro-cognitive stimuli/input to fascia and thus affect its function (and potentially even its structure). Specifically of interest are “top-down” neural mechanisms associated with MI that may be capable of influencing fascial tissue [166,198]. Empiric evidence of such interacting processes and mechanisms between MI and fascia would provide important scientific and clinical merits in scientific investigations into topics such as fascia-targeted attentional focus and fascial awareness [166,196,199–201] through MI. Fig. 1 summarizes the various suggested paths that could link MI and fascia.

5. Fascial mental imagery (FMI) and fascial dynamic neuro-cognitive imagery (FDNI)

Fascial mental imagery (FMI) is what we propose as a general term for describing an MI subtype that specifically focuses on the various aspects of fascial tissue, including, but not limited to, its location, structure, physiology, and movement. One approach to FMI is dynamic neuro-cognitive imagery (DNI; also known as “The Franklin Method”) [68,89,91,202–205], with fascial DNI (FDNI) [206] being the division that specifically targets fascia and its dynamic structure and function. FDNI uses various MI modalities (e.g., visual, kinesthetic) and types (e.g., anatomical, physiological, biomechanical, and metaphorical) [204], as well as other neuro-cognitive strategies such as self-talk [207,208] and self-touch [209], and combines them with movement. Such a combination aims to promote one's awareness and embodiment of the fascial tissue as well as fascia-mindful movement, with the goals of improving motor and non-motor functions, body schema, and MI ability, as well as reducing pain. Specifically, FDNI promotes the individual's awareness towards fascia and changes in its perception through self-noticing and focusing attention to it. Further, it offers images and metaphors to illustrate fascial composition, function, and

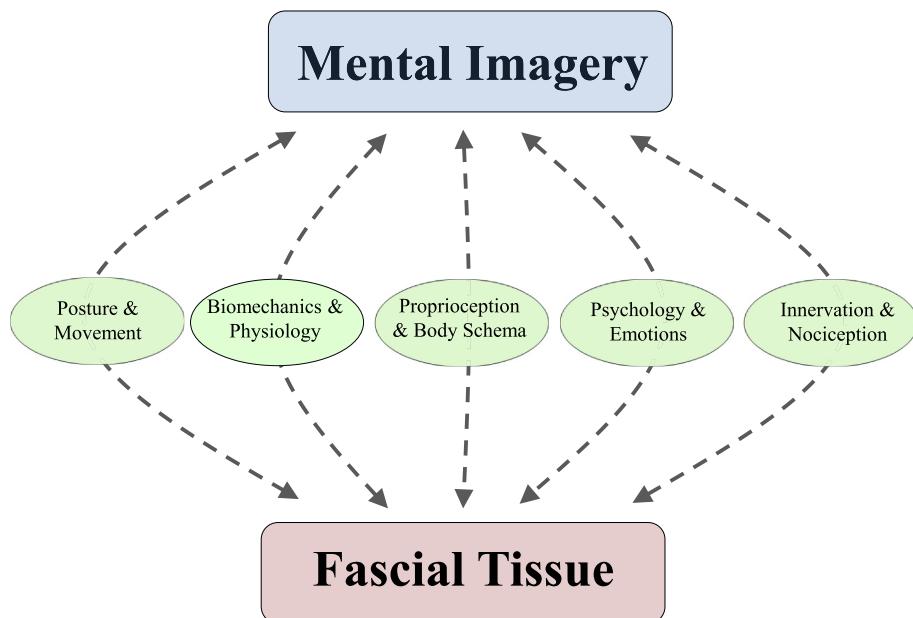


Fig. 1. Potential paths linking MI and fascial tissue.

three-dimensional movement. For example, the FDNI metaphor of “dancing fibroblasts” (i.e., the fibroblast cells holding hands together and dancing happily; Fig. 2) directs one’s attention toward the fascial tissue cells connectivity and mobility within performance of movement.

Doing so, FDNI may result in enhanced fascial awareness due to increased afferent information from it.

By integrating both MI and specific fascia-targeted movements and exercises, FDNI’s potential to affect fascia and muscles, both



Fig. 2. “Dancing fibroblasts”: FDNI metaphorical imagery. (Drawn by Eric Franklin; All rights reserved).

individually and together, is likely to be greater [25,210] than using MI alone, as it is the case of motor imagery practice [18,24]. A greater potential for affecting fascial tissue of the combination of MI with movement, as offered by FDNI, compared to MI solely, may be explained by (a) the somatic motor command (i.e., efferent input) potentially being less likely inhibited [37] and (b) fascial shortening and thickening potentially being impeded [211]. Furthermore, given our proposed paths of how MI and fascial tissue may interact, we also propose hypothetical FDNI-specific mechanisms of effect.

- 1) **Biomechanical.** Fascia-focused body biomechanics, motor patterns, and mindful movement could promote fascial mobility and flexibility. Specifically, FDNI may facilitate fascial mobility and fascia layers sliding through potentially changing fascial and muscle activation patterns, including stimulating the production or retention of lubricants between fascial fibers or layers [37].
- 2) **Neuro-Sensory.** FDNI may assist in increasing quantity and quality of afferent input from fascia and facilitate the establishment of additional afferent and efferent neural pathways. Specifically, FDNI may affect spinal reflexes and corticospinal excitability. Such enhanced neural activation could contribute to, among others, improved proprioceptive signaling from fascia.
- 3) **Psychological.** FDNI increases one's knowledge and understanding of fascial structure and function and directs one's attention internally to their body in general—and fascial tissue in particular—thus potentially contributing to enhanced fascial awareness, interoception, body image, and body schema.

6. Summary

With current therapeutic approaches to fascia mostly being agent-dependent [19,20,131], there is a need for innovative patient- or individual-centered approaches for ameliorating the fascial component in movement and therapies. Such approaches will increase individuals' motivation and engagement and direct their attention to desired components of performance or behavioral outcomes. This paper suggests that MI, and specifically FDNI, could serve as such an approach. To recommend further scientific inquiries interrelating MI and fascia, this paper has focused on developing science-based conceptualization for the linkages between these two elements as a first step towards designing and conducting empirical experiments. Such a research path could offer meaningful insights towards innovative perspectives within fascia research, therapy, and rehabilitation, and would open a door to novel non-pharmaceutical therapeutics and advanced and updated movement retraining approaches for fascia for preventive, rehabilitative, and performance enhancement purposes. Further, MI, and specifically FDNI given its emphasis on proprioception, could serve as an appropriate method for investigating neuro-cognitive mechanisms (e.g., motor planning and control) associated with fascial tissue and allow for further explorations into the beneficial effects of MI on fascial tissue. This paper suggests that combining movement and MI, such as offered by FDNI, may specifically benefit fascial mobility (and thus movement in general) via numerous motor, cognitive, and psychological channels. Such an approach could be of specific relevance for rehabilitation and prevention of various fascia-related disabling conditions, such as fibromyalgia, low back pain, Dupuytren disease, and adhesive capsulitis [9,19,101,167].

Acknowledgment

The authors would like to thank Dr. Rita Durant for her contribution to the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ctcp.2020.101193>.

[org/10.1016/j.ctcp.2020.101193](https://doi.org/10.1016/j.ctcp.2020.101193).

References

- [1] M.P. Cote, L.M. Murray, M. Knikou, Spinal control of locomotion: individual neurons, their circuits and functions, *Front. Physiol.* 9 (2018) 784.
- [2] A.S. Therrien, A.J. Bastian, The cerebellum as a movement sensor, *Neurosci. Lett.* 688 (2019) 37–40.
- [3] M. Bayot, K. Dujardin, C. Tard, L. Defebvre, C.T. Bonnet, E. Allart, et al., The interaction between cognition and motor control: a theoretical framework for dual-task interference effects on posture, gait initiation, gait and turning, *Neurophysiol. Clin.* 48 (6) (2018) 361–375.
- [4] K.Z.H. Li, L. Bherer, A. Mirelman, I. Maidan, J.M. Hausdorff, Cognitive involvement in balance, gait and dual-tasking in aging: a focused review from a neuroscience of aging perspective, *Front. Neurol.* 9 (2018) 913.
- [5] I.P. Rolf, *Rolfing: Reestablishing the Natural Alignment and Structural Integration of the Human Body for Vitality and Well-Being*, Healing Arts Press, Rochester, Vermont, 1989.
- [6] R. Schleip, D.G. Muller, Training principles for fascial connective tissues: scientific foundation and suggested practical applications, *J. Bodyw. Mov. Ther.* 17 (1) (2013) 103–115.
- [7] A. Ljungqvist, M.P. Schwennus, N. Bachl, M. Collins, J. Cook, K.M. Khan, et al., International Olympic Committee consensus statement: molecular basis of connective tissue and muscle injuries in sport, *Clin. Sports Med.* 27 (1) (2008) 231–239.
- [8] L. Schultz, R. Feitis, *The Endless Web Fascial Anatomy and Physical Reality*, North Atlantic Books, Barkeley, California, 1996.
- [9] M. Zugel, C.N. Maganaris, J. Wilke, K. Jurkat-Rott, W. Klingler, S.C. Wearing, et al., Fascial tissue research in sports medicine: from molecules to tissue adaptation, injury and diagnostics: consensus statement, *Br. J. Sports Med.* 52 (23) (2018) 1497.
- [10] G.A. Malanga, E.J. Cruz Colon, Myofascial low back pain: a review, *Phys. Med. Rehabil. Clin.* 21 (4) (2010) 711–724.
- [11] T. Taguchi, U. Hoheisel, S. Mense, Dorsal horn neurons having input from low back structures in rats, *Pain* 138 (1) (2008) 119–129.
- [12] D.A. Bednar, F.W. Orr, G.T. Simon, Observations on the pathomorphology of the thoracolumbar fascia in chronic mechanical back pain, A microscopic study, *Spine* 20 (10) (1995) 1161–1164.
- [13] U. Hoheisel, T. Taguchil, R.D. Treedel, S. Mensel, Nociceptive input from the rat thoracolumbar fascia to lumbar dorsal horn neurones, *Eur. J. Pain* 15 (8) (2011) 810–815.
- [14] H.M. Langevin, K.J. Sherman, Pathophysiological model for chronic low back pain integrating connective tissue and nervous system mechanisms, *Med. Hypotheses* 68 (1) (2007) 74–80.
- [15] L.F. Koziol, D. Budding, N. Andreassen, S. D'Arrigo, S. Bulgheroni, H. Imamizu, et al., Consensus paper: the cerebellum's role in movement and cognition, *Cerebellum* 13 (1) (2014) 151–177.
- [16] A.A. Sokolov, R.C. Miall, R.B. Ivry, The Cerebellum: adaptive prediction for movement and cognition, *Trends Cognit. Sci.* 21 (5) (2017) 313–332.
- [17] T. Mulder, Motor imagery and action observation: cognitive tools for rehabilitation, *J. Neural. Transm.* 114 (10) (2007) 1265–1278.
- [18] R. Dickstein, J.E. Deutsch, Motor imagery in physical therapist practice, *Phys. Ther.* 87 (7) (2007) 942–953.
- [19] R. Schleip, Fascial plasticity – a new neurobiological explanation: Part 2, *J. Bodyw. Mov. Ther.* 7 (2) (2003) 104–116.
- [20] R. Schleip, Fascial plasticity – a new neurobiological explanation: Part 1, *J. Bodyw. Mov. Ther.* 7 (1) (2003) 11–19.
- [21] C. Stecco, S. Adstrum, G. Hedley, R. Schleip, C.A. Yucesoy, Update on fascial nomenclature, *J. Bodyw. Mov. Ther.* 22 (2) (2018) 354.
- [22] C. Stecco, R. Schleip, A fascia and the fascial system, *J. Bodyw. Mov. Ther.* 20 (1) (2016) 139–140.
- [23] P. Holmes, C. Calmels, A neuroscientific review of imagery and observation use in sport, *J. Mot. Behav.* 40 (5) (2008) 433–445.
- [24] M. Lotze, U. Halsband, Motor imagery, *J. Physiol. Paris* 99 (4–6) (2006) 386–395.
- [25] A. Guillot, K. Moschberger, C. Collet, Coupling movement with imagery as a new perspective for motor imagery practice, *Behav. Brain Funct.* 9 (2013) 8.
- [26] A.C. ter Host, J. Cole, R. van Lier, B. Steenbergen, B, The effect of chronic deafferentation on mental imagery: a case study, *PLoS One* 7 (8) (2012), e42742.
- [27] A.G. Renault, M. Auvray, G. Parseilhan, R.C. Miall, J. Cole, F.R. Sarlegna, Does proprioception influence human spatial cognition? a study on individuals with massive deafferentation, *Front. Psychol.* 9 (2018) 1322.
- [28] M.I. Posner, S.E. Petersen, The attention system of the human brain, *Annu. Rev. Neurosci.* 13 (1990) 25–42.
- [29] A.C. Nobre, J.T. Coull, P. Maquet, C.D. Frith, R. Vandenberghe, M.M. Mesulam, Orienting attention to locations in perceptual versus mental representations, *J. Cognit. Neurosci.* 16 (3) (2004) 363–373.
- [30] R.M. Hardwick, S. Caspers, S.B. Eickhoff, S.P. Swinnen, Neural correlates of action: comparing meta-analyses of imagery, observation, and execution, *Neurosci. Biobehav. Rev.* 94 (2018) 31–44.
- [31] M. Jeannerod, The representing brain neural correlates of motor intention and imagery, *Sci. Brain Behav.* 17 (1994) 187–245.
- [32] N. Callow, L. Hardy, The relationship between the use of kinaesthetic imagery and different visual imagery perspectives, *J. Sports Sci.* 22 (2) (2004) 167–177.

- [33] A. Abraham, A. Dunsky, R. Dickstein, The effect of motor imagery practice on élevé performance in adolescent female dance students: a randomized controlled trial, *J. Imagery Res. Sport Phys. Activ.* 12 (2017) 20160006.
- [34] A. Abraham, A. Dunsky, R. Dickstein, Motor imagery practice for enhancing élève performance among professional dancers: a pilot study, *Med. Probl. Perform. Ar.* 31 (3) (2016) 132–139.
- [35] C.J. Olsson, L. Nyberg, Motor imagery: if you can't do it, you won't think it, *Scand. J. Med. Sci. Sports* 20 (5) (2010) 711–715.
- [36] R.C. Helmich, F.P. de Lange, I. Toni, Posture influences motor imagery: an fMRI study, *Neuroimage* 33 (2006) 609–617.
- [37] A. Guillot, C. Tolleron, C. Collet, Does motor imagery enhance stretching and flexibility? *J. Sports Sci.* 28 (3) (2010) 291–298.
- [38] J. Munzert, K. Zentgraf, R. Stark, D. Vaitl, Neural activation in cognitive motor processes: comparing motor imagery and observation of gymnastic movements, *Exp. Brain Res.* 188 (3) (2008) 437–444.
- [39] F. Filimon, J.D. Nelson, D.J. Hagler, M.I. Sereno, Human cortical representations for reaching: mirror neurons for execution, observation, and imagery, *Neuroimage* 37 (4) (2007) 1315–1328.
- [40] S. Hetu, M. Gregoire, A. Sainpoint, M.P. Coll, F. Eugene, P.E. Michon, et al., The neural network of motor imagery: an ALE meta-analysis, *Neurosci. Biobehav. Rev.* 37 (5) (2013) 930–949.
- [41] A. Guillot, C. Collet, Duration of mentally simulated movement: a review, *J. Mot. Behav.* 37 (1) (2005) 10–20.
- [42] R. Dickstein, A. Dunsky, E. Marcovitz, Motor imagery for gait rehabilitation in post-stroke hemiparesis, *Phys. Ther.* 84 (12) (2004) 1167–1177.
- [43] R.S. Burhans, C.L. Richman, D.B. Bergey, Mental imagery training: effects on running speed performance, *Int. J. Sport Psychol.* 19 (1) (1988) 26–37.
- [44] P. Post, S. Muncie, D. Simpson, The effects of imagery training on swimming performance: an applied investigation, *J. Appl. Sport Psychol.* 24 (3) (2012) 323–337.
- [45] A. Guillot, F. Lebon, D. Rouffet, S. Champely, J. Doyon, C. Collet, Muscular responses during motor imagery as a function of muscle contraction types, *Int. J. Psychophysiol.* 66 (1) (2007) 18–27.
- [46] F. Di Renzo, Y. Blache, T.F. Kanthack, K. Monteil, C. Collet, A. Guillot, Short-term effects of integrated motor imagery practice on muscle activation and force performance, *Neuroscience* 305 (2015) 146–156.
- [47] A. Blair, C. Hall, G. Leyshon, Imagery effects on the performance of skilled and novice soccer players, *J. Sports Sci.* 11 (2) (1993) 95–101.
- [48] R. Abdollahipour, G. Wulf, R. Psotta, M. Palomo Nieto, Performance of gymnastics skill benefits from an external focus of attention, *J. Sports Sci.* 33 (17) (2015) 1807–1813.
- [49] J. Annett, Imagery and motor processes, *Br. J. Psychol.* 86 (2) (1995) 161–167.
- [50] V.K. Ranganathan, V. Siemionow, J.Z. Liu, V. Sahgal, G.H. Yue, From mental power to muscle power—gaining strength by using the mind, *Neuropsychologia* 42 (7) (2004) 944–956.
- [51] I. Vergeer, J. Roberts, Movement and stretching imagery during flexibility training, *J. Sports Sci.* 24 (2) (2006) 197–208.
- [52] S. Grosprêtre, F. Lebon, C. Papaxanthis, A. Martin, New evidence of corticospinal network modulation induced by motor imagery, *J. Neurophysiol.* 115 (3) (2016) 1279–1288.
- [53] S. Grosprêtre, C. Ruffino, F. Lebon, Motor imagery and cortico-spinal excitability: a review, *Eur. J. Sport Sci.* 16 (3) (2016) 317–324.
- [54] D.J. Wright, J. Williams, P.S. Holmes, Combined action observation and imagery facilitates corticospinal excitability, *Front. Hum. Neurosci.* 8 (2014) 951.
- [55] L. Padiga, G. Buccino, L. Craighero, L. Fogassi, V. Gallesse, G. Pavesi, Corticospinal excitability is specifically modulated by motor imagery: a magnetic stimulation study, *Neuropsychologia* 37 (2) (1999) 147–158.
- [56] F. Lebon, W.D. Byblow, C. Collet, A. Guillot, C.M. Stinear, The modulation of motor cortex excitability during motor imagery depends on imagery quality, *Eur. J. Neurosci.* 35 (2) (2012) 323–331.
- [57] C.M. Stinear, W.D. Byblow, M. Steyvers, O. Levin, S.P. Swinnen, Kinesthetic, but not visual, motor imagery modulates corticomotor excitability, *Exp. Brain Res.* 168 (2006) 157–164.
- [58] S. Facchini, W. Muellbacher, F. Battaglia, B. Boroojerdi, M. Hallett, Focal enhancement of motor cortex excitability during motor imagery: a transcranial magnetic stimulation study, *Acta Neurol. Scand.* 105 (3) (2002) 146–151.
- [59] J. Munzert, B. Lorey, K. Zentgraf, Cognitive motor processes: the role of motor imagery in the study of motor representations, *Brain Res. Rev.* 60 (2) (2009) 306–326.
- [60] M. Slimani, D. Tod, H. Chaabene, B. Miarka, K. Chamari, Effects of mental imagery on muscular strength in healthy and patient participants: a systematic review, *J. Sci. Med. Sport* 15 (3) (2016) 434–450.
- [61] G. Yue, S.L. Wilson, K.J. Cole, W.G. Darling, W.T.C. Yuh, Imagined muscle contraction training increases voluntary neural drive to muscle, *Int. J. Psychophysiol.* 10 (3) (1996) 198–208.
- [62] F.C. Bakker, M.S.J. Boschker, T. Chung, Changes in muscular activity while imagining weight lifting using stimulus or response propositions, *J. Sport Exerc. Psychol.* 18 (3) (1996) 313–324.
- [63] S. Yahagi, T. Kasai, Facilitation of motor evoked potentials (MEPs) in first dorsal interosseous (FDI) muscle is dependent on different motor images, *Electroencephalogr. Clin. Neurophysiol.* 109 (5) (1998) 409–417.
- [64] W.H. Park, S. Li, No graded responses of finger muscles to TMS during motor imagery of isometric finger forces, *Neurosci. Lett.* 494 (3) (2011) 255–259.
- [65] B.D. Hale, The effects of internal and external imagery on muscular and ocular concomitants, *J. Sport Psychol.* 4 (1982) 379–387.
- [66] W.X. Yao, V.K. Ranganathan, D. Alexandre, V. Siemionow, G.H. Yue, Kinesthetic imagery training of forceful muscle contractions increases brain signal and muscle strength, *Front. Hum. Neurosci.* 7 (2013) 561.
- [67] G. Yue, K.J. Cole, Strength increases from the motor program: comparison of training with maximal voluntary and imagined muscle contractions, *J. Neurophysiol.* 67 (5) (1992) 1114–1123.
- [68] T. Heiland, R. Rovetti, Examining effects of Franklin method metaphorical and anatomical mental images on college dancers' jumping height, *Res. Dance Educ.* 14 (2) (2013) 141–161.
- [69] M.O. Frenkel, D.S. Herzig, F. Gebhard, J. Mayer, C. Becker, T. Einsiedel, Mental practice maintains range of motion despite forearm immobilization: a pilot study in healthy persons, *J. Rehabil. Med.* 46 (3) (2014) 225–232.
- [70] J.G. Williams, J.L. Odley, M. Callaghan, Motor imagery boosts proprioceptive neuromuscular facilitation in the attainment and retention of range-of-motion at the hip joint, *J. Sci. Med. Sport* 3 (3) (2004) 160–166.
- [71] C. Hanrahan, I. Vergeer, Multiple uses of mental imagery by professional modern dancers, *Imagin., Cognit. Pers.* 20 (3) (2000) 231–255.
- [72] K. Oishi, T. Kasai, T. Maeshima, Autonomic response specificity during motor imagery, *J. Physiol. Anthropol. Appl. Hum. Sci.* 19 (6) (2000) 255–261.
- [73] O. Bolliet, C. Collet, A. Dittmar, Autonomic nervous system activity during actual and mentally simulated preparation for movement, *Appl. Psychophysiol. Biofeedback* 30 (1) (2005) 11–20.
- [74] C. Collet, F. Di Renzo, N. El Hoyek, A. Guillot, Autonomic nervous system correlates in movement observation and motor imagery, *Front. Hum. Neurosci.* 7 (2013) 415.
- [75] Y. Wang, W.P. Morgan, The effect of imagery perspectives on the psychophysiological responses to imagined exercise, *Behav. Brain Res.* 52 (2) (1992) 167–174.
- [76] J. Decety, The neurophysiological basis of motor imagery, *Behav. Brain Res.* 77 (1–2) (1996) 45–52.
- [77] C. Papadelis, C. Kourtidou-Papadeli, P. Bamidis, M. Albani, Effects of imagery training on cognitive performance and use of physiological measures as an assessment tool of mental effort, *Brain Cognit.* 64 (1) (2007) 74–85.
- [78] E.V. Monsma, L.Y. Overby, The relationship between imagery and competitive anxiety in ballet auditions, *J. Dance Med. Sci.* 8 (1) (2004) 11–18.
- [79] A. Paivio, Cognitive and motivational functions of imagery in human performance, *Can. J. Appl. Sport Sci.* 10 (4) (1985) 225–285.
- [80] M. Bonnet, J. Decety, M. Jeannerod, J. Requin, Mental simulation of an action modulates the excitability of spinal reflex pathways in man, *Brain Res. Cogn. Brain Res.* 5 (3) (1997) 221–228.
- [81] T. Aoyama, F. Kaneko, The effect of motor imagery on gain modulation of the spinal reflex, *Brain Res.* 1372 (2011) 41–48.
- [82] P.J. Lang, A bio-informational theory of emotional imagery, *Psychophysiology* 16 (6) (1979) 495–512.
- [83] S. Li, D.G. Kamper, J.A. Stevens, W.Z. Rymer, The effect of motor imagery on spinal segmental excitability, *J. Neurosci.* 27 (2004) 9674–9680.
- [84] R. Hashimoto, J.C. Rothwell, Dynamic changes in corticospinal excitability during motor imagery, *Exp. Brain Res.* 125 (1) (1999) 75–81.
- [85] F. Helm, W. Marinovic, B. Kruger, J. Munzert, S. Riek, Corticospinal excitability during imagined and observed dynamic force production tasks: effortfulness matters, *Neuroscience* 290 (2015) 398–405.
- [86] K.A. Martin, C.R. Hall, Using mental imagery to enhance intrinsic motivation, *J. Sport Exerc. Psychol.* 17 (1995) 54–69.
- [87] M.R. Beauchamp, S.R. Bray, J.G. Albinson, Pre-competition imagery, self-efficacy and performance in collegiate golfers, *J. Sports Sci.* 20 (9) (2002) 697–705.
- [88] F. Lebon, A. Guillot, C. Collet, Increased muscle activation following motor imagery during the rehabilitation of the anterior cruciate ligament, *Appl. Psychophysiol. Biofeedback* 37 (1) (2012) 45–51.
- [89] A. Abraham, A. Hart, I. Andrade, M.E. Hackney, Dynamic neuro-cognitive imagery (DNI)TM improves mental imagery ability, disease severity, and motor and cognitive functions in people with Parkinson's disease, *Neural Plast.* 14 (2018) 6168507.
- [90] A. Abraham, A. Hart, R. Dickstein, M.E. Hackney, Will you draw me a pelvis?" dynamic neuro-cognitive imagery improves pelvic schema and graphic-metric representation in people with Parkinson's disease: a randomized controlled trial, *Complement. Ther. Med.* 43 (2019) 28–35.
- [91] A. Abraham, R. Gose, R. Schindler, B. H Nelson, M.E. Hackney, Dynamic neuro-cognitive imagery (DNITM) improves developed performance, kinematics, and mental imagery ability in university-level dance students, *Front. Psychol.* 10 (2019) 382.
- [92] J. Driskell, C. Copper, A. Moran, Does mental practice enhance performance? a meta-analysis, *J. Appl. Psychol.* 79 (1994) 481–492.
- [93] J. Taylor, S. Taylor, Pain education and management in the rehabilitation from sport injury, *Sport Psychol.* 12 (1998) 68–88.
- [94] K.J. Bowering, N.E. O'Connell, A. Tabor, M.J. Catley, H.B. Leake, G.L. Moseley, The effects of graded motor imagery and its components on chronic pain: a systematic review and meta-analysis, *J. Pain* 14 (1) (2013) 3–13.
- [95] M.S. Volz, V. Suarez-Contreras, A.L. Portilla, F. Fregni, Mental imagery-induced attention modulates pain perception and cortical excitability, *BMC Neurosci.* 16 (2015) 15.
- [96] F. Fardo, M. Allen, E.M. Jegindo, A. Angrilli, A. Roepstorff, Neurocognitive evidence for mental imagery-driven hypoalgesic and hyperalgesic pain regulation, *Neuroimage* 120 (2015) 350–361.
- [97] K. MacIver, D.M. Lloyd, S. Kelly, N. Roberts, T. Nurmikko, Phantom limb pain, cortical reorganization and the therapeutic effect of mental imagery, *Brain* 131 (8) (2008) 2181–2191.

- [98] G.L. Moseley, Graded motor imagery is effective for long-standing complex regional pain syndrome: a randomised controlled trial, *Pain* 108 (1) (2004) 192–198.
- [99] P. Morasso, M. Casadio, V. Mohan, F. Rea, J. Zenzeri, Revisiting the body-schema concept in the context of whole-body postural-focal dynamics, *Front. Hum. Neurosci.* 9 (2015) 83.
- [100] C. Stecco, O. Gagey, A. Belloni, A. Pozzuoli, A. Porzionato, V. Macchi, et al., Anatomy of the deep fascia of the upper limb. Second part: study of innervation, *Morphologie* 91 (292) (2007) 38–43.
- [101] R. Schleip, W. Klingler, F. Lehmann-Horn, Active fascial contractility: fascia may be able to contract in a smooth muscle-like manner and thereby influence musculoskeletal dynamics, *Med. Hypotheses* 65 (2) (2005) 273–277.
- [102] V. Wright, Stiffness: a review of its measurement and physiological importance, *Physiotherapy* 59 (4) (1973) 107–111.
- [103] R.J. Johns, V. Wright, Relative importance of various tissues in joint stiffness, *J. Appl. Physiol.* 17 (1962) 824–828.
- [104] S. Adstrum, G. Hedley, R. Schleip, C. Stecco, C.A. Yucesoy, Defining the fascial system, *J. Bodyw. Mov. Ther.* 21 (1) (2017) 173–177.
- [105] R. Schleip, H. Jager, W. Klingler, What is 'fascia'? a review of different nomenclatures, *J. Bodyw. Mov. Ther.* 16 (4) (2012) 496–502.
- [106] A. Schmitt-Graff, A. Desmouliere, G. Gabbiani, Heterogeneity of myofibroblast phenotypic features: an example of fibroblastic cell plasticity, *Virchows Arch.* 425 (1) (1994) 3–24.
- [107] J. Dawidowicz, N. Matysiak, S. Szotek, K. Maksymowicz, Telocytes of fascial structures, in: X. Wang, D. Cretoiu (Eds.), *Telocytes, Adv. Exp. Med. Biol.*, 913, Springer, Singapore, 2016.
- [108] C. Stecco, C. Fede, V. Macchi, A. Porzionato, L. Petrelli, C. Biz, et al., The fasciacites: a new cell devoted to fascial gliding regulation, *Clin. Anat.* 31 (5) (2018) 667–676.
- [109] M. Kumka, J. Bonar, Fascia: a morphological description and classification system based on a literature review, *J. Can. Chiropr. Assoc.* 56 (3) (2012) 179–191.
- [110] K.S. Leffler, J.R. Thompson, G.W. Cundiff, J.L. Buller, L.J. Burrows, M.A. Schon Ybarra, Attachment of the rectovaginal septum to the pelvic sidewall, *Am. J. Obstet. Gynecol.* 185 (1) (2001) 41–43.
- [111] J.A. Ashton-Miller, D. Howard, J.O. DeLancey, The functional anatomy of the female pelvic floor and stress continence control system, *Scand. J. Urol. Nephrol. Suppl.* 207 (2001) 1–7, 106–125.
- [112] P.P. Purslow, Muscle fascia and force transmission, *J. Bodyw. Mov. Ther.* 14 (4) (2010) 411–417.
- [113] M. Tian, R.D. Herbert, P. Hoang, S.C. Gandevia, L.E. Bilston, Myofascial force transmission between the human soleus and gastrocnemius muscles during passive knee motion, *J. Appl. Physiol.* 113 (4) (1985) 517–523, 2012.
- [114] M.L. Gatton, M.J. Pearcey, G.J. Pettet, J.H. Evans, A three-dimensional mathematical model of the thoracolumbar fascia and an estimate of its biomechanical effect, *J. Biomech.* 43 (14) (2010) 2792–2797.
- [115] P.J. Barker, K.T. Guggenheim, I. Grkovic, C.A. Briggs, D.C. Jones, C.D. Thomas, et al., Effects of tensioning the lumbar fasciae on segmental stiffness during flexion and extension: young Investigator Award winner, *Spine* 31 (4) (2006) 397–405.
- [116] G.R. Ebenbichler, L.I. Oddsson, J. Kollmitzer, Z. Erim, Sensory-motor control of the lower back: implications for rehabilitation, *Med. Sci. Sports Exerc.* 33 (11) (2001) 1889–1898.
- [117] B.L. Riemann, S.M. Lephart, The sensorimotor system, Part II: the role of proprioception in motor control and functional joint stability, *J. Athl. Train.* 37 (1) (2002) 80–84.
- [118] D.G. Lee, L.J. Lee, L. McLaughlin, Stability, continence and breathing: the role of fascia following pregnancy and delivery, *J. Bodyw. Mov. Ther.* 12 (4) (2008) 333–348.
- [119] P.P. Purslow, The structure and functional significance of variations in the connective tissue within muscle, *Comp. Biochem. Physiol., Part A Mol. Integr. Physiol.* 133 (4) (2002) 947–966.
- [120] M.L. Gatton, M.J. Pearcey, G.J. Pettet, J.H. Evans, A three-dimensional mathematical model of the thoracolumbar fascia and an estimate of its biomechanical effect, *J. Biomech.* 43 (14) (2010) 2792–2797.
- [121] S. Gracovetsky, Is the lumbodorsal fascia necessary? *J. Bodyw. Mov. Ther.* 12 (3) (2008) 194–197.
- [122] A. Gefen, Stress analysis of the standing foot following surgical plantar fascia release, *J. Biomech.* 35 (5) (2002) 629–637.
- [123] A. Vleeming, A.L. Pool-Goudzwaard, R. Stoeckart, J.P. van Wingerden, C. J. Snijders, The posterior layer of the thoracolumbar fascia. Its function in load transfer from spine to legs, *Spine* 7 (20) (1995) 753–758.
- [124] C. Stecco, O. Gagey, V. Macchi, A. Porzionato, R. De Caro, R. Aldegheri, et al., Tendinous muscular insertions onto the deep fascia of the upper limb. First part: anatomical study, *Morphologie* 91 (292) (2007) 29–37.
- [125] A. Viladot, J.C. Lorenzo, J. Salazar, A. Rodriguez, The subtalar joint: embryology and morphology, *Foot Ankle* 5 (2) (1984) 54–66.
- [126] J. Schwobbel, H.B. Coslett, Evidence for multiple, distinct representations of the human body, *J. Cognit. Neurosci.* 17 (4) (2005) 543–553.
- [127] H.M. Langevin, J.R. Fox, C. Koptiuch, G.J. Badger, A.C. Greenan-NaumannN, A. Bouffard, et al., Reduced thoracolumbar fascia shear strain in human chronic low back pain, *BMC Musculoskel. Disord.* 12 (2011) 203.
- [128] B. Bordoni, F. Marelli, Emotions in motion: myofascial interoception, complement, *Med. Reserve* 24 (2) (2017) 110–113.
- [129] E. Cathcart, T. McSweeney, R. Johnston, H. Young, D.J. Edwards, Immediate biomechanical, systemic, and interoceptive effects of myofascial release on the thoracic spine: a randomised controlled trial, *J. Bodyw. Mov. Ther.* 23 (1) (2019) 74–81.
- [130] R. Schleip, G. Gabbiani, J. Wilke, I. Naylor, B. Hinz, A. Zorn, et al., Fascia is able to actively contract and may thereby influence musculoskeletal dynamics: a histochemical and mechanographic investigation, *Front. Physiol.* 10 (2019) 336.
- [131] L. Stecco, *Fascial Manipulation for Musculoskeletal Pain*, PICCIN, Italy, 2004.
- [132] I. Darby, O. Skalli, G. Gabbiani, Alpha-smooth muscle actin is transiently expressed by myofibroblasts during experimental wound healing, *Lab. Invest.* 63 (1) (1990) 21–29.
- [133] M. Spector, Musculoskeletal connective tissue cells with muscle: expression of muscle actin in and contraction of fibroblasts, chondrocytes, and osteoblasts, *Wound Repair Regen.* 9 (1) (2002) 11–18.
- [134] J.J. Tomasek, G. Gabbiani, B. Hinz, C. Chaponnier, R.A. Brown, Myofibroblasts and mechano-regulation of connective tissue remodelling, *Nat. Rev. Mol. Cell Biol.* 3 (5) (2002) 349–363.
- [135] R. Schleip, I.L. Naylor, I. Ursu, W. Melzer, A. Zorn, H.J. Wilke, et al., Passive muscle stiffness may be influenced by active contractility of intramuscular connective tissue, *Med. Hypotheses* 66 (1) (2006) 66–71.
- [136] N. Masood, N.I.L. Naylor, Effect of adenosine on rat superficial and deep fascia and the effect of heparin on the contractile responses, *Br. J. Pharmacol.* 113 (1994) 112.
- [137] R.A. Brand, C.M. Stanford, How connective tissues temporally process mechanical stimuli, *Med. Hypotheses* 42 (2) (1994) 99–104.
- [138] T.A. Jarvinen, L. Jozsa, P. Kannus, T.L. Jarvinen, M. Jarvinen, Organization and distribution of intramuscular connective tissue in normal and immobilized skeletal muscles. An immunohistochemical, polarization and scanning electron microscopic study, *J. Muscle Res. Cell Motil.* 23 (3) (2002) 245–254.
- [139] J.C. Guimbertea, J.P. Delage, D.A. McGrouther, J.K. Wong, The microvacuolar system: how connective tissue sliding works, *J. Hand Surg. Eur.* 35 (8) (2010) 614–622.
- [140] M. Loukas, M.M. Shojai, T. Thurston, V.L. Jones, S. Linganna, R.S. Tubbs, Anatomy and biomechanics of the vertebral aponeurosis part of the posterior layer of the thoracolumbar fascia, *Surg. Radiol. Anat.* 30 (2) (2008) 125–129.
- [141] F.J. Clark, P.R. Burgess, Slowly adapting receptors in cat knee joint: can they signal joint angle? *J. Neurophysiol.* 38 (6) (1975) 1448–1463.
- [142] P. Grigg, B.J. Greenspan, Response of primate joint afferent neurons to mechanical stimulation of knee joint, *J. Neurophysiol.* 40 (1) (1977) 1–8.
- [143] A. Rossi, P. Grigg, Characteristics of hip joint mechanoreceptors in the cat, *J. Neurophysiol.* 47 (6) (1982) 1029–1042.
- [144] P.E. Williams, G. Goldspink, Connective tissue changes in immobilised muscle, *J. Anat.* 138 (Pt 2) (1984) 343–350.
- [145] O. Gagey O. Bonfait, C. Gillot, F. Mazas, Anatomie fonctionnelle et mécanique de l'élévation du bras, *Rev. Chir. Orthopédique* 74 (1988) 209–217.
- [146] P.A. Huijing, Epimuscular myofascial force transmission: a historical review and implications for new research. International Society of Biomechanics Muybridge Award Lecture, Taipei, 42, *J. Biomech.* 5 (1) (2007) 9–21, 2009.
- [147] P.A. Huijing, Epimuscular myofascial force transmission between antagonistic and synergistic muscles can explain movement limitation in spastic paresis, *J. Electromogr. Kinesiol.* 17 (6) (2007) 708–724.
- [148] P.A. Huijing, R.W. van de Langenberg, J.J. Meesters, G.C. Baan, Extramuscular myofascial force transmission also occurs between synergistic muscles and antagonistic muscles, *J. Electromogr. Kinesiol.* 17 (6) (2007) 680–689.
- [149] R. Schleip, T.W. Findley, L. Chaitow, P.A. Huijing, *Fascia: the Tensional Network of the Human Body*, Churchill Livingstone/Elsevier, London, UK, 2012.
- [150] R. Schleip, *Fascia as a sensory organ*, in: R. Schleip, A. Baker (Eds.), *Fascia in Sport and Movement*, Handspring Publishing, Edinburgh, U.K., 2015.
- [151] M. von Diring, K.H. Andres, Topography and fine structure of proprioceptors in the hagfish, *Myxine glutinosa*, *Eur. J. Morphol.* 32 (2–4) (1994) 248–256.
- [152] C. Stecco, V. Macchi, A. Porzionato, A. Morra, A. Parenti, A. Stecco, et al., The ankle retinacula: morphological evidence of the proprioceptive role of the fascial system, *Cells Tissues Organs* 192 (3) (2010) 200–210.
- [153] N. Simmonds, P. Miller, H. Gemmill, A theoretical framework for the role of fascia in manual therapy, *J. Bodyw. Mov. Ther.* 16 (1) (2012) 83–93.
- [154] C. Stecco, A. Porzionato, V. Macchi, A. Stecco, E. Vigato, A. Parenti, The expansions of the pectoral girdle muscles onto the brachial fascia: morphological aspects and spatial disposition, *Cells Tissues Organs* 3 (188) (2008) 320–329.
- [155] M. Benjamin, The fascia of the limbs and back—a review, *J. Anat.* 214 (1) (2009) 1–18.
- [156] L. Yahia, S. Rhalmi, N. Newman, M. Isler, Sensory innervation of human thoracolumbar fascia. an immunohistochemical study, *Acta Orthop. Scand.* 63 (2) (1992) 195–197.
- [157] V. Sanchis-Alfonso, E. Rosello-Sastre, Immunohistochemical analysis for neural markers of the lateral retinaculum in patients with isolated symptomatic patellofemoral malalignment. A neuroanatomic basis for anterior knee pain in the active young patient, *Am. J. Sports Med.* 28 (5) (2000) 725–731.
- [158] C.A. Avila Gonzalez, M. Driscoll, R. Schleip, S. Wearing, E. Jacobson, T. Findley, Frontiers in fascia research, *J. Bodyw. Mov. Ther.* 22 (4) (2018) 873–880.
- [159] H.M. Langevin, Connective tissue: a body-wide signaling network? *Med. Hypotheses* 66 (6) (2006) 1074–1077.
- [160] W. Gibson, L. Arendt-Nielsen, T. Taguchi, K. Mizumura, T. Graven-Nielsen, Increased pain from muscle fascia following eccentric exercise: animal and human findings, *Exp. Brain Res.* 194 (2) (2009) 299–303.
- [161] P.C. Rowe, K.R. Fontaine, R.L. Violand, Neuromuscular strain as a contributor to cognitive and other symptoms in chronic fatigue syndrome: hypothesis and conceptual model, *Front. Physiol.* 4 (2013) 115.

- [162] A. Schilder, U. Hoheisel, W. Magerl, J. Benrath, T. Klein, R.D. Treede, Sensory findings after stimulation of the thoracolumbar fascia with hypertonic saline suggest its contribution to low back pain 155 (2) (2014) 222–231.
- [163] A. Schilder, W. Magerl, T. Klein, R.D. Treede, Assessment of pain quality reveals distinct differences between nociceptive innervation of low back fascia and muscle in humans, *Pain Rep* 3 (3) (2018) e662.
- [164] H.M. Langevin, D. Stevens-Tuttle, J.R. Fox, G.J. Badger, N.A. Bouffard, M.H. Krag, et al., Ultrasound evidence of altered lumbar connective tissue structure in human subjects with chronic low back pain, *BMC Musculoskel. Disord.* 10 (2009) 151–151.
- [165] B. Bordoni, F. Marelli, B. Morabito, B. Sacconi, The indeterminable resilience of the fascial system, *J. Integr. Med.* 15 (5) (2017) 337–343.
- [166] B. Bordoni, M. Simonelli, The awareness of the fascial system, *Cureus* 10 (2018) e3397.
- [167] G.L. Liptan, Fascia: a missing link in our understanding of the pathology of fibromyalgia, *J. Bodyw. Mov. Ther.* 14 (1) (2010) 3–12.
- [168] J. van der Wal, The architecture of the connective tissue in the musculoskeletal system – an often overlooked functional parameter as to proprioception in the locomotor apparatus, *Int. J. Ther. Massage Bodywork* 2 (4) (2009) 9–23.
- [169] H. Maas, G.C. Baan, P.A. Huijing, Intermuscular interaction via myofascial force transmission: effects of tibialis anterior and extensor hallucis longus length on force transmission from rat extensor digitorum longus muscle, *J. Biomech.* 34 (7) (2001) 927–940.
- [170] P. Huijing, Muscular force transmission: a unified, dual or multiple system? A review and some explorative experimental results, *Arch. Physiol. Biochem.* 107 (4) (1999) 292–311.
- [171] P.A. Huijing, Muscle as a collagen fiber reinforced composite: a review of force transmission in muscle and whole limb, *J. Biomech.* 32 (4) (1999) 329–345.
- [172] R.L. Gajdosik, Passive extensibility of skeletal muscle: review of the literature with clinical implications, *Clin. Biomech.* 16 (2) (2001) 87–101.
- [173] T. Hotfiel, B. Swoboda, S. Krinner, C. Grim, M. Engelhardt, M. Uder, et al., Acute effects of lateral thigh foam rolling on arterial tissue perfusion determined by spectral Doppler and power Doppler ultrasound, *J. Strength Condit. Res.* 31 (4) (2017) 893–900.
- [174] S.J. Aboodarda, R.M. Greene, D.T. Philpott, R.S. Jaswal, G.Y. Millet, D.G. Behm, The effect of rolling massage on the excitability of the corticospinal pathway, *Appl. Physiol. Nutr. Metabol.* 43 (4) (2018) 317–323.
- [175] B. Hinz, S.H. Phan, V.J. Thannickal, M. Prunotto, A. Desmouliere, J. Varga, et al., Recent developments in myofibroblast biology: paradigms for connective tissue remodeling, *Am. J. Pathol.* 180 (4) (2012) 1340–1355.
- [176] R. Schleip, L. Duerselen, A. Vleeming, I.L. Naylor, F. Lehmann-Horn, A. Zorn, et al., Strain hardening of fascia: static stretching of dense fibrous connective tissues can induce a temporary stiffness increase accompanied by enhanced matrix hydration, *J. Bodyw. Mov. Ther.* 16 (1) (2012) 94–100.
- [177] H.M. Langevin, K.N. Storch, M.J. Cipolla, S.L. White, T.R. Buttolph, D.J. Taatjes, Fibroblast spreading induced by connective tissue stretch involves intracellular redistribution of alpha- and beta-actin, *Histochem. Cell Biol.* 125 (5) (2006) 487–495.
- [178] H.M. Langevin, N.A. Bouffard, G.J. Badger, J.C. Iatridis, A.K. Howe, Dynamic fibroblast cytoskeletal response to subcutaneous tissue stretch ex vivo and in vivo, *Am. J. Physiol. Cell Physiol.* 288 (3) (2005) C747–C756.
- [179] B. Hinz, G. Gabbiani, Mechanisms of force generation and transmission by myofibroblasts, *Curr. Opin. Biotechnol.* 14 (5) (2003) 538–546.
- [180] L. Chaitow, New evidence of a dynamic fascial maintenance and self-repair process, *J. Bodyw. Mov. Ther.* 20 (4) (2016) 701–703.
- [181] J.D. Humphrey, E.R. Dufresne, M.A. Schwartz, Mechanotransduction and extracellular matrix homeostasis, *Nat. Rev. Mol. Cell Biol.* 15 (12) (2014) 802–812.
- [182] W.L. Neuhuber, The innervation of fascial tissues: focus on thin-caliber afferents and sympathetic efferents, in: T. Liem T, P. Tozzi, A. Chila (Eds.), *Fascia in the Osteopathic Field*, Handspring Publishing, Edinburgh, Scotland, 2017, pp. 339–350.
- [183] J. Tesarz, U. Hoheisel, B. Wiedenhofer, S. Mense, Sensory innervation of the thoracolumbar fascia in rats and humans, *Neuroscience* 194 (2011) 302–308.
- [184] P.G. Pavan, A. Stecco, R. Stern, C. Stecco, Painful connections: densification versus fibrosis of fascia, *Curr. Pain Headache Rep.* 18 (8) (2014) 441.
- [185] D. Caligore, M. Mustilea, G. Spalletta, G. Baldassarre, Action observation and motor imagery for rehabilitation in Parkinson's disease: a systematic review and an integrative hypothesis, *Neurosci. Biobehav. Rev.* 72 (2017) 210–222.
- [186] G. D'Alessandro, F. Cerritelli, P. Cortelli, Sensitization and interoception as key neurological concepts in osteopathy and other manual medicines, *Front. Neurosci.* 10 (2016) 100.
- [187] C. Deschaumes-Molinaro, A. Dittmar, E. Vernet-Maury, Autonomic nervous system response patterns correlate with mental imagery, *Physiol. Behav.* 51 (5) (1992) 1021–1027.
- [188] K. Oishi, T. Maeshima, Autonomic nervous system activities during motor imagery in elite athletes, *J. Clin. Neurophysiol.* 21 (3) (2004) 170–179.
- [189] T.P. Pinto, M.M.R. Ramos, T. Lemos, C.D. Vargas, L.A. Imbiriba, Is heart rate variability affected by distinct motor imagery strategies? *Physiol. Behav.* 1 (177) (2017) 189–195.
- [190] J.H. Mitchell, R.F. Schmidt, Cardiovascular reflex control by afferent fibers from skeletal muscle receptors, in: J.T. Shepherd, et al. (Eds.), *Handbook of Physiology*, Section 2, Volume III Part 2, 2011, p. 623.
- [191] M.F. Barnes, The basic science of myofascial release: morphologic change in connective tissue, *J. Bodyw. Mov. Ther.* 1 (4) (1997) 231–238.
- [192] P. Tozzi, Does fascia hold memories? *J. Bodyw. Mov. Ther.* 18 (2) (2014) 259–265.
- [193] M. Sterling, G. Jull, A. Wright, Cervical mobilisation: concurrent effects on pain, sympathetic nervous system activity and motor activity, *Man. Ther.* 6 (2) (2001) 72–81.
- [194] J.P. Delaney, K.S. Leong, A. Watkins, D. Brodie, The short-term effects of myofascial trigger point massage therapy on cardiac autonomic tone in healthy subjects, *J. Adv. Nurs.* 37 (4) (2002) 364–371.
- [195] M.J. Alter, *Science of Flexibility*, Human Kinetics, Champaign, IL, 2004.
- [196] E. Franklin E, A. Abraham, Fascial wake-up with dynamic neuro-cognitive imagery (conference workshop). The British Fascia Symposium, Solihull, UK, 2018.
- [197] E. Franklin, A. Abraham, The use of fascia-targeted dynamic neuro-cognitive imagery ("The Franklin Method") in sports performance (conference workshop). 2nd International Congress on Connective Tissues in Sports Medicine, Ulm, Germany, 2017.
- [198] A. Gazzaley, A.C. Nobre, Top-down modulation: bridging selective attention and working memory, *Trends Cognit. Sci.* 16 (2) (2012) 129–135.
- [199] M. Kimmel, C. Iran, M.A. Luger, Bodywork as systemic and inter-enactive competence: participatory process management in Feldenkrais(R) Method and Zen Shiatsu, *Front. Psychol.* 5 (2014) 1424.
- [200] E. Franklin, *Inner Focus Outer Strength*, Princeton Book Company, Hightstown, NJ, 2006.
- [201] E. Franklin, *Grow Young Daily: the Power of Imagery for Healthy Cells and Timeless Beauty*, Dog Ear, Indianapolis, 2016.
- [202] E. Franklin, *The Art and Science of Cueing*, OPTP, 2016.
- [203] E. Franklin, *Dynamic Alignment through Imagery*, Human Kinetics, Champaign, IL, 2012.
- [204] E. Franklin, *Dance Imagery for Technique and Performance*, Human Kinetics, Champaign, IL, 2014.
- [205] T.L. Heiland, R. Rovetti, J. Dunn, Effects of visual, auditory, and kinesthetic imagery interventions on dancers' plié arabesques, *J. Imagery Res. Sport Phys. Activ.* 7 (1) (2012). Article 5.
- [206] E. Franklin, *Fascia Release and Balance: Franklin Method Ball and Imagery Exercises*, OPTP, 2014.
- [207] A. Hatzigeorgiadis, N. Zourbanos, E. Galanis, Y. Theodorakis, Self-talk and sports performance: a meta-analysis, *Perspect. Psychol. Sci.* 6 (4) (2011) 348–356.
- [208] Y. Theodorakis, R. Weinberg, P. Natsis, I. Douma, P. Kazakas, The effects of motivational versus instructional self-talk on imporving motor performance, *Sport Psychol.* 14 (2000) 253–272.
- [209] H.E. van Stralen, M.J. van Zandvoort, H.C. Dijkerman, The role of self-touch in somatosensory and body representation disorders after stroke, *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 366 (2011) 3142–3152.
- [210] A. Fusco, M. Iosa, M.C. Gallotta, S. Paolucci, C. Baldari, L. Guidetti, Different performances in static and dynamic imagery and real locomotion. An exploratory trial, *Front. Hum. Neurosci.* 8 (2014) 760.
- [211] T. Findley, H. Chaudhry, A. Stecco, M. Roman, Fascia research—a narrative review, *J. Bodyw. Mov. Ther.* 16 (1) (2012) 67–75.