INVESTIGATION OF KINESIO TAPING EFFECTS ON MUSCULAR MECHANICS WITH NOVEL IMAGING ANALYSES

by

Seda Yıldız

B.S., in Physical Therapy and Rehabilitation, Hacettepe University, 2009

M.S., in Sports Physiotherapy, Hacettepe University, 2012

Submitted to the Institute of Biomedical Engineering
in partial fulfillment of the requirements
for the degree of
Doctor
of
Philosophy

Boğaziçi University

2022

ACKNOWLEDGMENTS

First of all, I would like to express my sincere gratitude to my advisor, Prof. Dr. Can Yücesoy, for his unending patience, unwavering encouragement and insightful guidance with regard to my research, academia and life in general.

Besides my advisor, I would like to thank the other members of my thesis committee; Prof. Dr. Tolga Aydoğ, Prof. Dr. Gül Baltacı and Assoc. Prof. Dr. Özgür Kocatürk for their invaluable comments and support in the completion of this thesis, and Assoc. Prof. Dr. Esin Öztürk Işık for her guidance to statistical topics.

Special thanks to my former university professors Nevin Ergun, Gül Baltacı and Kezban Bayramlar who have supported me to be a better clinician, researcher and scientist during all my PhD years.

I would also like to acknowledge my exceedingly reliable and supportive labmates: Uluç Pamuk, Arda Arpak, Agah Karakuzu, Cemre Su Kaya Keleş , Ramazan Tarık Türksoy, Eda Biricik, Fatma Turan, Beste İmamoğlu and Alper Atal. Uluç Pamuk and Arda Arpak, in particular, deserve my gratitude for their collaboration, technical support and notable patience during my experiments.

Moreover, I could not have stayed sane without the support of my beloved friends Yasemin Gökpınar, Zeynep Seçil, Gülşah Barğı, Gülşah Başandaç, Tuğçe Kalaycıoğlu, Songül Budak, Müberra Tanrıverdi and Seher Özyürek who steadfastly believed in, loved, supported and helped pick me back up when I fell during the more trying periods of this academic endeavor. I greatly value their friendship and I deeply appreciate their belief in me, and their support and care helped me overcome setbacks and stay focused on my graduate studies.

I would also like to thank Kevin John Palmer II for encouraging me in the first year of my PhD to continue, and for later giving me the support, power and love to be able to see my dissertation through to the end. An additional thanks is needed for the Palmer family as they hosted me in their lovely home, made me feel welcome, and provided me with nutritious food and one of the most suitable libraries imaginable.

Last but not least, I want to acknowledge that none of this would have been possible without the love and support of my family. To my mother Sebahat, my father Aziz, my sisters Sema and Selin and their endless patience, help and edifying influence- I wouldn't have been able to do it without you. And to my lovely niece, Mavi Yıldız, your presence blessed me with immeasurable joy that allowed me to continue even in the most arduous of times. I would like to express my heart-felt gratitude to all of them.

ACADEMIC ETHICS AND INTEGRITY STATEMENT

I, Seda Yıldız, hereby certify that I am aware of the Academic Ethics and Integrity Policy issued by the Council of Higher Education (YÖK) and I fully acknowledge all the consequences due to its violation by plagiarism or any other way.

Name : ______________________________

Signature: ______________________________

Date: ______________________________

ABSTRACT

INVESTIGATION OF KINESIO TAPING EFFECTS ON MUSCULAR MECHANICS WITH NOVEL IMAGING ANALYSES

Kinesio Taping (KT) is an elastic therapeutic tape that is utilized for the prevention and treatment of various neuromusculoskeletal disorders and sports injuries. Despite its widespread use especially improving muscular function, there is a lack of understanding of its effects on muscular mechanics. In vivo analyzes of muscle mechanical response to external loads caused by KT is crucial to define its unknown action mechanism and to improve this kind of therapeutic approaches. Due to continuity of fascial system by muscular connective structures (epimysium, perimysium, and endomysium) and the interaction between muscle fibers and extra cellular matrix, loading effects imposed by KT are likely to be distributed to deep muscular fascia via force transmission. This thesis aims to address these effects by tensiomyography (TMG) and combination of Magnetic Resonance Imaging (MRI) based deformation and Diffusion Tensor Imaging (DTI) based fiber tracking analyzes. TMG analysis revealed that KT caused an increase in muscle tissue stiffness and a decrease in muscle rate of force development. Results of MRI-based deformation and DTI-based fiber tracking indicated that KT-imposed external loads lead to along-fascicle shear strains and along-fascicle length changes in terms of lengthening and shortening and strain distribution were heterogeneous for all subjects. In summary, non-invasive in vivo analyzes were used to evaluate the effects of KT on muscular mechanics. Among these analyzes, the TMG method was used to measure the effects of KT on the mechanical properties of the muscle, while the MRI and DTI methods were used to measure the effects of KT on along-muscle fascicle shear strains and length changes.

Keywords: Kinesio Taping, Tensiomyography, Diffusion Tensor Imaging, Magnetic Resonance Imaging, Myofascial Loads.

ÖZET

KİNEZYO BANTLAMANIN KAS MEKANİĞİ ÜZERİNE OLAN ETKİLERİNİN GÜNCEL GÖRÜNTÜLEME ANALİZLERİ İLE İNCELENMESİ

Kinezyo Bantlama (KB), çeşitli nöromuskuloskeletal hastalıkların ve spor yaralanmalarının önlenmesi ve tedavisinde kullanılan elastik terapötik bir banttır. Kas fonksiyonunu arttırmaya yönelik yaygın kullanımına rağmen, kas mekaniği üzerindeki etkilerinin anlaşılmasında yetersizlik vardır. KB'nin neden olduğu dış yüklere kas mekanik yanıtının in vivo analizleri, bilinmeyen etki mekanizmasını tanımlamak ve bu tür terapötik yaklaşımları geliştirmek için çok önemlidir. Fasyal sistemin müsküler bağ yapılar (epimisyum, perimisyum ve endomisyum) ile sürerliliği ve kas lifleri ile hücre dışı matris arasındaki etkileşim nedeniyle, KB tarafından oluşturulan yüklerin etkilerinin kuvvet iletimi yoluyla derin kas fasyasına dağılması muhtemeldir. Bu tez, bu etkileri Tensiyomyografi (TMG) ve Manyetik Rezonans Görüntüleme (MRG) tabanlı deformasyon ve Difüzyon Tensor Görüntüleme (DTG) tabanlı fiber izleme analizlerinin kombinasyonu ile ele almayı amaçlamaktadır. TMG analizi KB'nin kas dokusu sertliğinde bir artışa ve kas kuvvet üretimi hızında bir azalmaya yol açtığını gösterdi. MRI tabanlı deformasyon ve DTG tabanlı fiber izleme sonuçları, KB tarafından uygulanan dış yüklerin fasikül boyunca kayma gerinimleri ve boy değişimi açısından uzama ve kısalma değişikliğine yol açtığını ve gerinim dağılımlarının tüm denekler için heterojen olduğunu gösterdi. Özetle, KB'nin kas mekaniği üzerine etkilerini değerlendirmek için girişimsel olmayan in vivo analizler kullanıldı. Bu analizlerden TMG yöntemi KB'nin kasın mekanik özellikleri üzerindeki etkilerini incelerken, MRG ve DTG yöntemleri kas boyunca fasikül kayma gerinimleri ve uzunluk değişiklikleri üzerindeki etkilerini ölçmek için kullanıldı.

Anahtar Sözcükler: Kinezyo Bantlama, Tensiyomyografi, Difüzyon Tensör Görüntüleme, Manyetik Rezonans Görüntüleme, Miyobağdokusal Yükler

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

μM	micrometer
mm	millimeter
cm	centimeter
m	meter
kg	kilogram
ms	millisecond
T	Tesla

LIST OF ABBREVIATIONS

Dm	Maximum Radial Displacement
Tc	Contraction Time
Td	Delay Time
Tr	Relaxation Time
Ts	Sustain Time
Vc	Velocity of Contraction
BMI	Body Mass Index
ROM	Range of Motion
KT	Kinesio Taping
Pre-KT	Before KT Application
Post-KT1	1 Day After KT Application
TMG	Tensiomyography
EMG	Electromyography
MRI	Magnetic Resonance Imaging
DTI	Diffusion Tensor Imaging
VMO	Vastus Medialis Obliquus
TA	Tibialis Anterior
ECM	Extracellular Matrix
SD	Standard Deviation
DIR	Deformable Image Resgistration
FA	Fractional Anisotrophy
FOV	Field of View
MFT	Myofascial Force Transmission
EMFT	Epimuscular Myofascial Force Transmission

1. OVERVIEW

1.1 Anatomy of Skeletal Muscle and Force Production

Skeletal muscles comprise 40 % of total human body mass and are responsible for protection of internal organs, locomotion, and force production. Having a very complex structure and various interacting components, skeletal muscle can be defined as a well-organized biomechanical device [1]. It is composed of muscle fibers (myofibers) and highly ordered extra-cellular matrix (ECM). Myofibers are the cells of skeletal muscles with a diameter about 10 μm to 100 μm and composed of several myofibrils which are approximately 15 mm long. Myofibers are surrounded by a loose ECM layer called endomysium which has a role in passive mechanical properties of muscle fibers and provides a connection between adjacent muscle fibers [2]. Several bundles of myofibers form muscle fascicles that are surrounded by more stout and less dense connective tissue layer of ECM called perimysium. To form a muscle, approximately 300 muscle fascicles are assembled together and comprise a muscle bundle. Each muscle is a separate organ and is covered by a thigh connective tissue layer of ECM called epimysium [3, 4] (Figure 1.1). Due to myofascial continuity, neighboring muscles are linked to each other with the epimysium [5].

Sarcomere is the smallest functional unit of the skeletal muscle (approximately 2.5 μm in resting muscle) and is serially arranged. Sarcomeres are composed of sets of contractile proteins called actin and myosin myofilaments that run parallel to muscle fiber axis and these myofilaments slide against each other during contraction and relaxation. Actin filaments are defined as thin filaments and are fixed to Z line or Z-disk that separates each sarcomere. A part of thin filament, I band (lighter area of a sarcomere) is shared between neighboring sarcomeres and is bisected by Z-disk. Myosin filaments are called as thick filaments. Dense A band (darker area of sarcomere) made up of these thick filaments located at the center of each sarcomere. H zone located in the midline of an A band is lighter due to the lack of actin myofilaments and divided

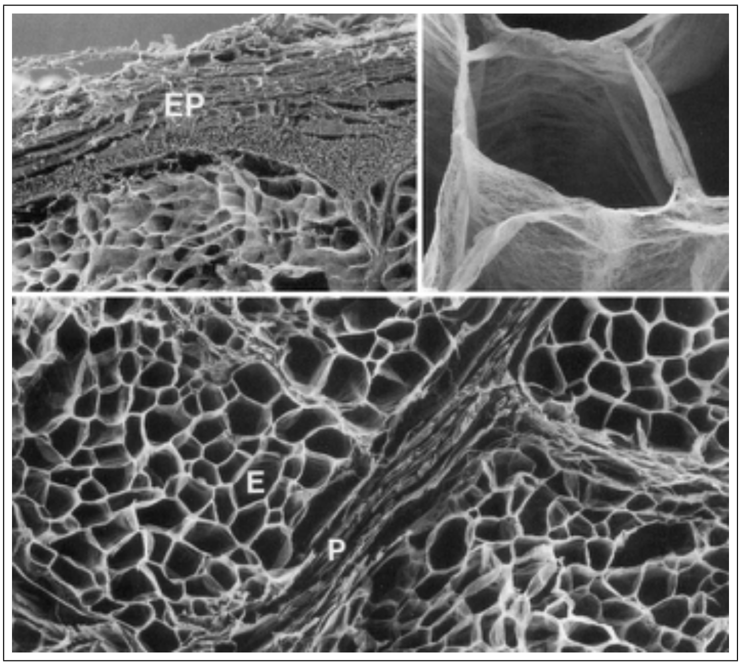

Figure 1.1 Ultrastructure of Intramuscular Connective Tissue; epimysium (EP), perimysium (P), endomysium (E) [4].

by M-line. The thin actin filaments are held together in a lateral array at the Z-disk while the M-line located in the middle of sarcomere interconnects the thick myosin filaments [6, 7, 1]. Titin is the third important protein inside a sarcomere. It is the largest molecule of the body and connects myosin filaments with the Z-disks [8]. Titin takes part in elastic stiffness of a muscle and is considered to function like a spring to help sarcomere to recoil back to its original length after contraction or stretch [7, 9] (Figure 1.2). Muscle contraction starts at the neuromuscular junction, the connection between motor neuron and muscle fiber. When there is an action potential in a motor neuron, acetylcholine is released at the neuromuscular junction. As a result contraction of the muscle fibers innervated by that motor neuron occur. More muscle fibers are contracted if more motor neurons are stimulated [10].

At a sarcomeric level, muscle contracts during a sequence of overlap between actin and myosin filaments and this mechanism is explained by Sliding Filament Theory. According to this theory, muscle contraction occurs as a result of thick and thin filaments glide on each other through cross bridge linkages. When active part of the actin filaments is interacted by myosin filament, contraction starts. Troponin and

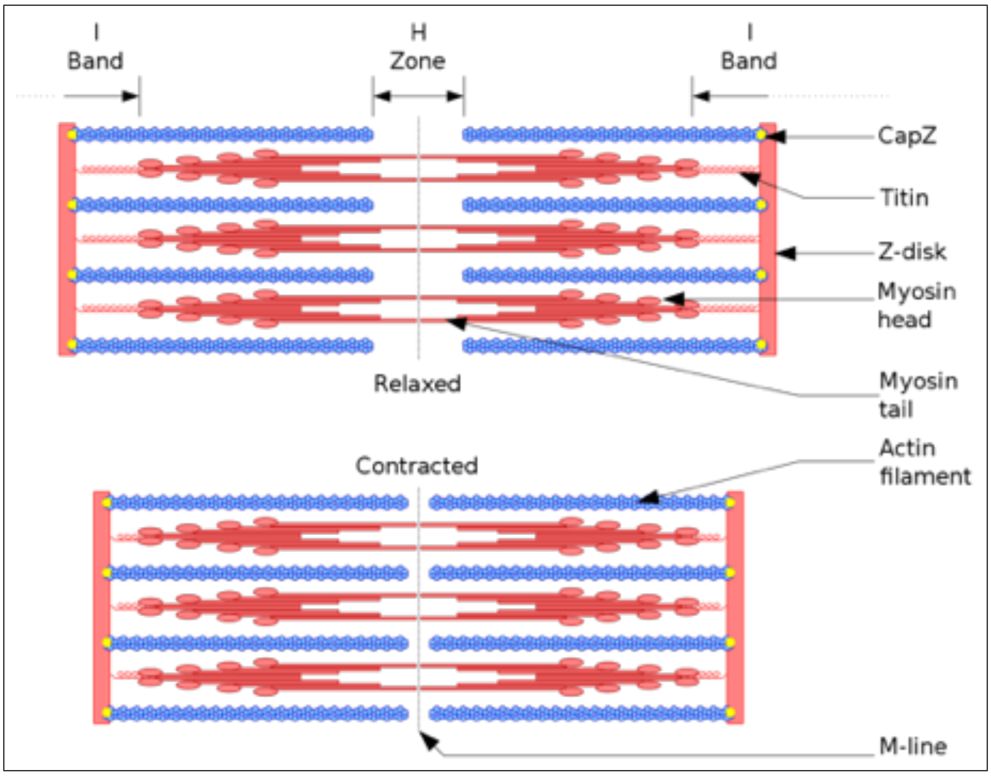

Figure 1.2 Structure of Sarcomere [9].

tropomyosin which are part of actin structure, are responsible for connection between actin and myosin filaments during contraction. While tropomyosin blocks actin and myosin interaction during rest of a muscle, troponin uncovers the active site of actin and by attachment of myosin head to this active site contraction of the muscle is initiated causing sarcomere length change. During concentric contraction, while A band remains constant in size, a variation is observed in I band length and it gets smaller likewise H-zone, hence sarcomere length decreases. On the other hand, during stretching, A band remains constant in size, while the width of the I band and H zone increases. As a consequence sarcomere lengthens [6, 7, 10].

Force production capacity of a muscle depends on its architectural parameters such as pennation angle, cross sectional area, fiber type distribution and sarcomere length [2]. Maximal muscular force is produced when the sarcomere is between 2-2.20 μm of its length and maximal actin myosin overlap observed in that length [11] (Figure 1.3). Additionally, number of serially distributed sarcomere which is translated into muscle fiber length is correlated to velocity of movement and force excursion capac-

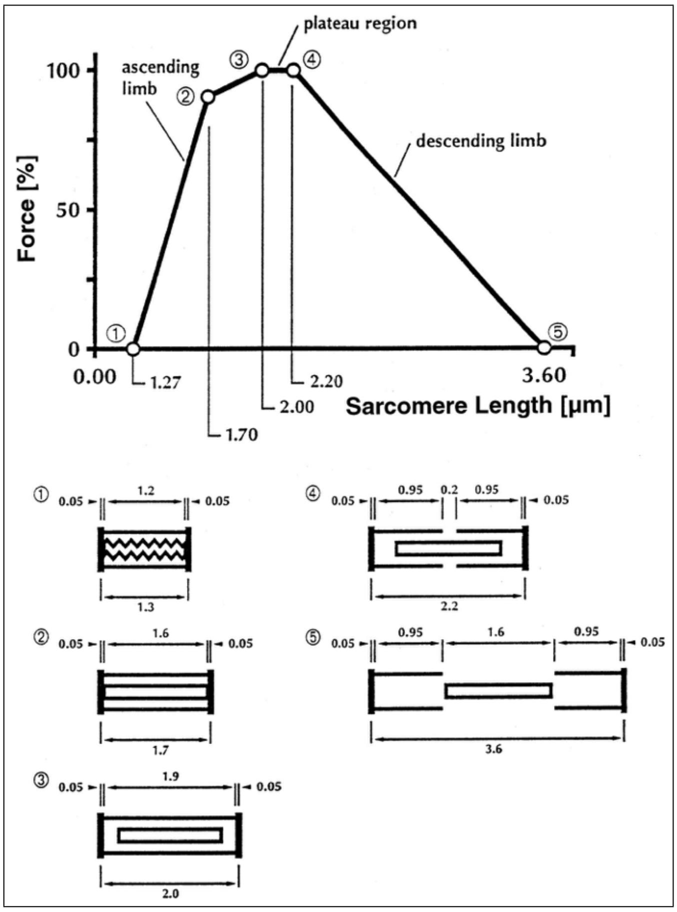

Figure 1.3 Force-Length Graph [11].

ity with fiber type distribution and pennation angle of the muscle [12, 13]. On the other hand, the number of parallelly distributed sarcomeres which means distribution of sarcomere length across different muscle fibers are directly related to force production capacity as it correlates with cross-sectional area [14]. Therefore, both number of serially and parallelly arranged sarcomeres are important for muscle force production. As skeletal muscle is a very adaptable tissue to existence or lack of mechanical load, distribution of sarcomeres in serial and parallel might be altered in conditions such as aging, lack of activity and nutrition, traumas or spaceflight. Hence, structural changes in muscle morphology can occur under these circumstances and force production capacity of a muscle may be diminished [15, 16, 17].

1.2 Structure of Fascial Tissue

Fascia is a dense, membranous continuum composed of irregular connective tissue which envelops, connects and separates muscles, bones, organs, neural pathways as well as other soft structures of the body exyending from head to toe. It is defined as 'a body-wide tensional force transmission network' at the first Facia Research Congress [18, 19]. The first layer of fascia is called as superficial fascia and is made up of multidirectional and non-uniform connective tissue fibers. This layer contains free nerve endings, Pacinian corpuscles and Rufini endings. Therefore, this layer is theorized to have effects on proprioception [20]. Deep fascia covers internal structures of the body such as bones, muscles, nerves and blood, and has role in motoneuronal coordination. Structurally, it has more hyaluronan than superficial fascia [21]. Due to having linkages between deep fascia and epimysium, perimysium and endomysium, during each muscle contraction a direct strain occurs along all fascial tissue layers [22]. Therefore, fascia provides structural support to musculoskeletal system mechanics and has an important role in force transmission. According to literature, biomechanical properties of fascia can be changed due to pathological conditions such as inflammation, traumas or injuries. Due to the connections of superficial fascia with deep fascia and extra-cellular matrix, any deficiency in these two fascial layers can affect movements of musculoskeletal system. Altered tensional state or thickness in the fascia might diminish fascial network and can cause a reduced joint mobility and lack of force transmission [23].Treatments such as manual therapy, dry needle, instrument assisted soft tissue mobilization or taping techniques are used to reduce fascial restrictions and improve fascial mobility.

1.3 Force Transmission and Myofascial Loads

Traditionally, myotendinous junction is thought to be the only site for the force transmission from skeletal muscles to bones and that is defined as myotendinous force transmission [24]. Recently, secondary pathways of force transmission between muscles and non-muscular tissues were found and this transmission is referred as myofascial force transmission (MFT) [5, 25]. As muscle is not an isolated tissue from its surroundings and fascial system is continuous with muscular connective tissue structures, MFT occurs between muscle fibers and extra-cellular matrix (ECM). Transmission extends from inner layers of ECM (endomysium and perimysium) [26] to outer ECM layer (epimysium) and further to neighboring muscle bellies [25]. Intramuscular MFT is defined as force transmission from muscle fiber to ECM; intermuscular MFT is defined as force transmission from ECM to adjacent muscle's ECM; extramuscular MFT is defined as force transmission from ECM of a muscle to bones and other non-muscular structures. Intermuscular and extramuscular MFT collectively known as epimuscular myofascial force transmission (EMFT) [27]. Central to this concept are myofascial loads, forces acting on muscle belly are transmitted deep into the muscle via fascial system [28]. Force alterations caused by relative positional changes between muscles is an indicator of myofascial load when their lengths are constant [29, 27], in different range of motion [30] and in active state [31]. Such myofascial loads distributed inside the muscle can affect mechanical equilibrium locally at different muscle parts. As an external load superficially on the skin, Kinesio Taping can be considered as myofascial load that might alter length distribution of sarcomeres both in parallel and serial and might affect length-force characteristics.

1.4 Kinesio Taping

Kinesio Tape (KT) is an elastic tape that is mainly used to prevent and treat neuromusculoskeletal disorders and sports injuries and enhance muscle performance [32, 33]. It is characterized by the ability to stretch up to 130% - 140% of its resting state and attempt to recoil back to its original length after application. Having approximately the same weight and the thickness, it purports the elastic properties of the skin [34]. The fabric of this specialized tape is air permeable and water resistant [35]. Therefore, it can be worn up to 3 - 5 days and can provide prolonged treatments [36].

KT is utilized in clinics for several conditions such as increasing blood and lymphatic circulation [37], decreasing pain [38], reducing swelling and lymphoedema [39], healing scar tissue [40], improving range of motion [41, 42], improving balance and functional performance [43], enhancing proprioceptive facilitation [44], increasing muscle strength [45], and providing muscular facilitation and inhibition [46]. Despite its common use, there is not any consensus about its effects and effect mechanism.

One of the proposed theories behind KT application effect mechanism is that KT elevates the space by lifting the skin and soft tissues which causes an increase in blood and lymphatic flow due to enlarged subcutaneous space [37]. Shim et al. [47] revealed with an animal experiment that KT caused wrinkles not only compressing the skin but also elevating the underlying space. They also reported there were positive effects on opening microvalves due to dynamic pressure change. This periodic compression and decompression to superficial and deep lymphatics might lead to an increase in circulation. Another effect mechanism of KT is attributed to neurological mechanism. According to that, KT application implements a pressure or continual stretching on the skin under the taped area which leads to external activation of cutaneous mechanoreceptors. Increased afferent impulses from skin receptors, joint capsule, ligaments and muscle spindle allow central nervous system to build better proprioceptive information [32]. In clinical practice, increased somatosensory stimulation may reduce pain, enhance athlete's postural control and facilitate their earlier return to activity [35]. Another study about pain inhibition posits that KT decreases pain via the gate control theory [48]. Afferent fibers for pain - A Delta fiber and C fiber - are smaller both in diameter and conduction velocity than afferent fiber from sensory neurons of touch-A Beta fiber. A Beta fiber, afferent fiber from sensory neurons of touch, is bigger in diameter and conduction velocity than fibers for pain including A Delta fiber and C fiber [49, 50]. Tactile stimulation provided by KT application may cause the firing of large-diameter afferent fibers that close the gate to pain signals transmitted by small-diameter afferent fibers [51]. This stimulation also leads a decrease in musculoskeletal pain and muscle soreness and improves muscle strength [52, 53].

In athletic courts and sports clinics, KT is widely used to improve muscular function. Muscular facilitation or inhibition effect of KT is explained by differences in taping technique, tension and adhering direction. An increase of muscle tonus occurs if KT is applied from origin to insertion of the muscle, which is referred as the facilitation technique. It is expected that the recoil effect of the tape may enhance muscle spindle reflex, facilitating the muscle's contraction toward an elevated tonus. In reverse situation, KT application from insertion to origin of muscle, recoil effect of the tape may restrain motor neurons by stretching the Golgi Tendon Organs at the distal end of muscle, which is referred as the inhibition technique [54, 33]. In addition, effects of KT on muscular function is also attributed to its effects on length-tension relationship of a muscle by altering actin myosin filament overlap of the sarcomere. [36, 55].

By reducing pain and improving muscular function, KT was found to be effective on the active range of motion (ROM), gait and function of patients who have osteoarthritis [56, 57]. In total knee replacement patients, KT was found to reduce swollen and pain and improve knee extension during postoperative rehabilitation sessions [58]. In another study investigating the effects of KT on pain during squat exercise in patellofemoral pain syndrome patients, significant reductions in pain level were observed after KT application [59]. Sensory effects of KT was considered to reduce pain by blocking afferent pain input. Therefore, KT helped individuals to have a better ROM and improved the quality of movement patterns. Moreover, the effects of KT on countermovement jumping performance on male athletes were analyzed and KT application on lower limb muscles was found to increase jump height in these particular group by improving neuromuscular performance [60].

Despite its common use in clinics and courts to modulate muscular force, the studies mainly have investigated neurosensory effects of KT and investigation of its effects on mechanical metrics of muscle (stiffness, shear, strain) have been sparse. Therefore, quantification of its mechanical effects bares great importance to understand its effects on ultrastructure of muscle and improve its clinical use.

1.5 Methodologies for Assessment of Muscular Mechanics in Muscle in Vivo

1.5.1 Tensiomyography

Tensiomyography (TMG) is a non-invasive tool that is developed to assess skeletal muscle mechanical and contractile properties consecutive to electrical stimuli. Specifically, TMG measures skeletal muscle thickening and low-frequency lateral oscillations of active skeletal muscle fibers due to electrical stimulation [61]. This method provides information about distribution of muscle fiber type [62], as well as muscle atrophy [61], damage [63], condition [64], functional symmetry [65, 66], contractile properties [67] and fatigue [64]. Additionally, TMG was found to be a sensitive measurement tool for assessing muscle force changes after various strength training programs [68]. Therefore, it is used to monitor the consequence of various exercise prescriptions and treatment approaches [68, 69, 70] and measure neuromuscular effects of different training loads on acute and chronic reactions of muscles [66]. Moreover, information obtained from TMG assessments is used to determine the most suitable type, intensity and frequency of a training protocol in order to decrease injuries and prepare the most effective training and recovery program [71].

TMG measurements are performed in a static and relaxed position with the participant in the supine or prone position, depending on the muscle being measured. No physical effort is required of the participant who is under evaluation [72]. The muscle belly is palpated during active contraction and marked with a dermatological pen according to the anatomical guide for the electromyographic muscle motor point prescription [73]. In order to detect enlargement of the muscle belly as a response to electrical stimulation, a digital displacement sensor (GK 40, Panoptik d.o.o., Ljubljana, Slovenia) with a spring of 0.17 mm-1 is positioned perpendicularly to the muscle being measured on the marked point. Two self-adhesive surface electrodes (5x5 cm) (Compex Medical SA, Ecublens, Switzerland) are placed distally and proximally around the sensor tip, approximately 5 cm apart from each other, to deliver a constant electrical stimulation produced with a TMG-S1 electrostimulator (Furlan Co. Ltd., Ljubljana, Slovenia). An isometric contraction is generated by the electrical stimulus and displacement-time curve recordings are obtained after each stimulation. The stimulation is performed under gradually increasing electrical current intensities until there is no change in displacement of the muscle belly. To prevent muscle fatigue, rest periods of 10 seconds were given between each measurement.

TMG measurement records maximal twitch response of the muscle after to electrical stimulation. A displacement-time curve is obtained at the end of each measurement [71]. The main outputs of TMG assessment extracted from the displacement-time curve are maximum radial displacement (Dm), contraction time (Tc), relaxation time (Tr), delay time (Td), sustain time (Ts) and velocity of contraction (Vc). Dm is the total distance in millimeters from rest to maximal contraction of the muscle and represents peak radial displacement of the muscle in transverse direction. The remaining five parameters are in the time domain. Tc represents time to peak tension and the duration of the interval between 10% and 90% of Dm. Tr is the duration required to return to a resting state back to rest after isometric contraction. Td is the duration of the interval between the start of electrical impulse and 10% Dm. Ts represents the duration of sustained contraction [67, 64]. Velocity of contraction (Vc) is not a direct TMG parameter and is calculated as the ratio of Dm/Tc [74]. Vc indicates the rate (mm/s) of contraction between 10% and 90% of maximal Dm [75]. In the case of a high muscular tone, Dm is decreased. Conversely, Dm is increased within individuals exhibiting low muscular tone. Decreased Dm is also associated with loss of strength and muscle power, resulting in a reduction in contraction velocity (Vc) and enhanced Tc [76]. When Dm is increased, explosive force increases involving high movement amplitude and muscle tonus decreases [66].The value of Tc is mainly attributed to the muscular rate of force production [62] and speed of twitch force generation [77]. It is also used to differentiate the distribution of fast muscle fiber type from slow one [67]. A low rate of Tc reveals the percentage of type 1 muscle fibers exceeds type 2 fibers [66]. Increased Tc is also correlated with a reduction in peak force, rate of force development and Dm [63]. Moreover, as the peak force and rate of force development decrease, Dm is similarly expected to decrease. Conversely, an increase in Tc is expected in such condition [63]. Tr is attributed to fatigue level [64, 75], with a higher value of Tr is associated with greater muscular fatigue [78, 79, 71]. The value of Vc on the other hand, is related to rate of force production [68]. Vc combines peak radial displacement with contraction time and yields information on twitch rate without being affected by changes in peak radial displacement [80].

1.5.2 Magnetic Resonance Imaging and Diffusion Tensor Imaging

Magnetic Resonance Imaging (MRI) is a non-invasive method with a high spatial resolution that is typically used in the clinical setting to obtain millimeter-order anatomical images. MRI produces multiplanar and three-dimensional data sets of soft tissue in vivo without producing harmful ionizing radiation. It uses the angular momentum of protons in H atoms within a magnetic field to form an image of the body part. As human body is primarily composed of fat and water which has many H atoms, when radiofrequency energy applied on tissues that contain free H nuclei during MRI acquisition, various signals within the constant magnetic field of an MRI scanner is produced. In vivo tissue movements are tracked and displacement of strain fields are quantified by MRI. Quantification of strain fields maintain knowledge about the architecture and mechanical response of skeletal muscle [81, 82]. Demons Algorithm which is an intensity-based, nonrigid and nonparametric image analysis technique is used for the calculation of in vivo strain and volume change. This algorithm relies on differences between gray scale values of consecutive voxels within each image and corresponding voxels [83].

Diffusion Tensor Image (DTI) is an MRI methodology that reveals the diffusivity of water molecules to the local environment in biological tissues by applying diffusion sensitizing gradients in different directions. DTI is used to provide information about tissue architecture (pennation angle and fiber length). Motion of the water molecules are restricted by biological structures such as cell membrane. The images obtained from DTI and their analysis have the ability to reveal pathways in which the water can move most obviously within a tissue structure [84]. For the investigation of skeletal muscles, this information helps identifying the direction of muscle fibers. With this method, the fiber direction strain values are obtained by turning the obtained strain field to the direction of the pulled tracts. Therefore, it is possible to analyze the distribution of the lengthening and shortening that occurs along each direction and the average strain values on each tract in three-dimensional and color-coded manner [85].

1.6 Aim of the Thesis

Based on the background summarized above and the need for improving the knowledge about KT mechanical effects on muscle, the thesis aims at following: (i) To investigate the effects of KT on muscle contractile properties by using TMG. (ii) To quantify local length changes along-muscle fascicle due to KT application by combining MRI-based deformation and DTI-based fiber tracking analyses.

1.7 List of Publications

1.7.1 Journal Publications

(i) Effects of Kinesio Taping on Muscle Contractile Properties: Assessment Using Tensiomyography. Yildiz S, Pamuk U, Baltaci G, Yucesoy CA J Sport Rehabil. 2022 Mar; 31(3):263−270.

1.7.2 Conference Proceedings

(i) Tensiomyographic Assessment of Changes In Muscle Tissue Stiffness Due to Kinesio Taping, S. Yildiz, U. Pamuk, G. Baltaci, C.A. Yucesoy, 31st Kinesio Taping Research Symposium, 7-8 October 2017, Honolulu, Hawai, USA.

(ii) Kinesio Taping Effects On Along-Muscle Fascicle Local Length Changes:

Magnetic Resonance And Diffusion Tensor Imaging Based Assessment, S. Yildiz, A. Arpak, A. Karakuzu, C.A. Yucesoy, 6th International Fascia Research Congress, 10-14 September 2022, Montreal, Canada.

2. EFFECTS OF KINESIO TAPING ON MUSCLE CONTRACTILE PROPERTIES: ASSESSMENT USING TENSIOMYOGRAPHY

2.1 Introduction

Kinesio taping (KT) is utilized in prevention and treatment of neuromusculoskeletal disorders and sports injuries [32]. KT is characterized by the tape's ability to stretch up to 130% to 140% of its original length and attempt to recoil back to its unstretched length after application, thereby deforming the underlying tissue. KT aims to, for example, increase range of motion and improve strength [42], as well as proprioceptive facilitation [44], muscular facilitation, and inhibition [46, 86]. The pressure or continual stretching of the skin on the taped area is thought to cause external activation of cutaneous mechanoreceptors within the central nervous system and an increase in muscle excitability [36]. However, considering field-related studies, although broad effects on, for example, gait and posture have been tested, evidence to link KT effects and actual reactions induced in targeted tissues remains limited. Recently, magnetic resonance imaging (MRI) analyses were used to assess such effects in high resolution, in terms of tissue length and volume changes [87]. The results revealed heterogeneous local stretching and shortening occurring in varying amplitudes and directions across different muscle parts. This confirms that KT does affect the targeted muscle, which can be quantified in terms of mechanical strain and is suggestive of active state effects. However, those effects remain limited to the relaxed state and such MRI analyses are computationally and time-wise very demanding. Studies on muscle contractile properties do exist but show contradicting KT effects. For example, Slupik et [86] showed that KT causes an increase in peak joint torque and electromyography (EMG) of vastus medialis muscle of healthy individuals and Hsu et al [88] showed an increase in lower trapezius muscle strength in athletes with shoulder impingement. However, Grześkowiak et al [89] and Lins et al [90] showed no significant KT effects on EMG of lumbar multifidus and longissimus thoracic muscles and EMG and peak knee torque of quadriceps muscles. Note that, EMG indicating recruitment of muscle groups [91]bares a broad meaning regarding KT effects on the target muscle's contractile properties whereas other metrics, such as torque and strength, which are actually in the joint level, are not determined solely by the target muscle. These metrics are therefore not sufficient for a consistent, muscle-specific and muscle-based understanding of KT effects in active state.

Because of constancy of muscle volume, longitudinal muscle fascicle length changes during contraction are accompanied by transverse deformations [92], which reflect on radial displacement of muscle belly [80]. In addition, by affecting actin-myosin overlap, KT is believed to affect force development [55] and changes in, for example, viscoelastic properties and Ca+2 transport can affect contraction metrics in the time domain [80]. Hence, metrics such as muscle radial displacement and contraction time characterizing muscle stiffness and rate of force development are direct indicators for changes in contractile properties of the targeted muscle due to KT. Tensiomyography (TMG) is a noninvasive assessment technique that measures such specific contractile properties of skeletal muscle belly upon electrically induced twitch contraction. This technique has been proven to be successful in assessing changes in muscle contractile properties [67] as a consequence of various exercise protocols and treatment approaches [68, 70], further allowing for interpreting effects of those on, for example, muscle fiber type distribution [62], atrophy [61], status [64], and fatigue [64]. In addition, post-processing of TMG data is much less demanding compared with, for example, MRI analyses in terms of technical skills and computation time. Therefore, TMG may provide an applicable clinical assessment tool that can be operationalized by the practitioner.

Based on above, although expected KT benefits do include effects on the target muscle's contractile properties, muscle-specific assessment of those with direct metrics is needed. Taking into account those expected benefits and muscle-specific effects shown by Pamuk and Yucesoy [87] in the relaxed state, we hypothesized that KT has effects on contractile properties of targeted muscle that can be quantified as changes in radial displacement and metrics in the time domain. The aim was to test this hypothesis using TMG.

2.2 Methods

Experimental procedures were in strict agreement with guidelines and regulations concerning human welfare and experimentation set forth by Turkish law, and approved by a Committee on Ethics of Human Experimentation at Acibadem University.

2.2.1 Participants

The study was performed in the performance laboratory of Acibadem Sport Rehabilitation Center. Eleven healthy subjects (4 males and 7 females) participated in the study. After a full explanation of the purpose and methodology, the subjects provided an informed consent. Prior to the experiment, a piece of tape was adhered to the participants' forearm and any allergic reaction was monitored for 10 minutes, which led to the exclusion of one participant. The participants' age range equaled 21 and 23 years (mean age = 22.1 [0.9] y) and body mass index (BMI) range equaled 18.1 and 23.5 (mean BMI = 20.2 [1.7] kg/m2). The exclusion criteria for the participants recruited among college students included neuro-muscular and musculoskeletal pathologies, trauma or surgery to the lower extremities, skin allergy to tape application, and physical activity changes that would have affected muscle tone during the study. General orthopedic physical therapy assessment (manual muscle tests, flexibility tests, and measurement of normal range of motion) for lower limb were done before measurement. The activity levels of the participants were 2 or 3 according to the Tegner activity scale; that is, they were not competitive in any kind of sport and they were not exercising regularly [93]. The activity level of 3 female and 2 male participants was 2, and for 4 female and 2 male participants it was 3. For 2 days prior to and 1 day following the first experimentation, the participants were instructed to avoid any exercise. During the 45-minute period following the KT application, they maintained a sitting position.

2.2.2 Experimental Procedures

2.2.2.1 Tensiomyography. TMG Measurements. All measurements were conducted by a TMG-trained physiotherapist. The participants were assessed in supine position with the help of a triangular foam cushion placed under the knee for ensuring a knee angle of 120°. They were asked to voluntarily extend their knees from 15° flexion to full extension, so that the vastus medialis obliquus (VMO) was palpated and located. The muscle belly was marked with a dermatological pen according to anatomical guide for the electromyographic muscle motor point prescription [73]. A digital displacement sensor (GK 40; Panoptik d.o.o., Ljubljana, Slovenia) with a known and fixed pretension was placed perpendicularly on the mark to record the radial displacement of VMO muscle belly. Two self-adhesive square (5x5 cm) surface electrodes were placed around the sensor tip distally and proximally, approximately 5 cm apart from each other (Figure 2.1A). Exact positions of the electrodes were also marked and kept constant during the experiment. Submaximal electrical stimulation (a single monophasic pulse of 1 ms duration) was triggered by a special electrical stimulator (TMG-S2; EMF-Furlan and Co, Ljubljana, Slovenian). The consequent bulging in the muscle belly was recorded (TMG-OK 3.0 software; TMG-BMC, Ljubljana, Slovenia).

The displacement-time curve as the output of TMG assessment is utilized for outcome measures and the maximal radial displacement (ie, the total distance from rest to maximal contraction of the muscle [in measured millimeters]) is studied as a central metric: After each twitch response, the stimulation current was increased in 10 mA increments until the change in radial displacement ceased. Subsequently, the mean of the values recorded during the 2 peak twitch responses was used for statistics. To prevent muscle fatigue, rest periods of 10 seconds were given between measurements [70]. In addition, metrics in the time domain, namely delay time and contraction time (ie, duration of the interval between the start of electrical impulse and 10%; and between 10% and 90% of maximal radial displacement, respectively), sustain time (ie, total duration of contraction), relaxation time (the duration till rest after cease of isometric contraction) [67, 64] and velocity of contraction, were studied. A typical TMG measurement chart and the aforementioned metrics are illustrated in Figure 2.1B. Note that velocity of contraction is not a direct TMG parameter, but is calculated as the ratio of maximal radial displacement and contraction time [74] representing the rate (in millimeters per second) of contraction between 10% and 90% of maximal radial displacement [75].

TMG measurements have been reported to have excellent interobserver, intrasession and between-day reliability and high validity and reproducibility for muscle's contractile properties [79, 62, 72]. Intraclass correlation coefficient for all metrics and testâretest intervals revealed good to excellent relative reliability ranging from .75 to .99 [94]. Independently of the evaluated muscles, high relative reliability for maximal radial displacement (.91-.99), moderate to high intraclass correlation coefficient for sustain time (.80-.96), contraction time (.70-.98) and relaxation time (.77-.93), and low to high intraclass correlation coefficient for delay time (.60-.98) was reported [95].

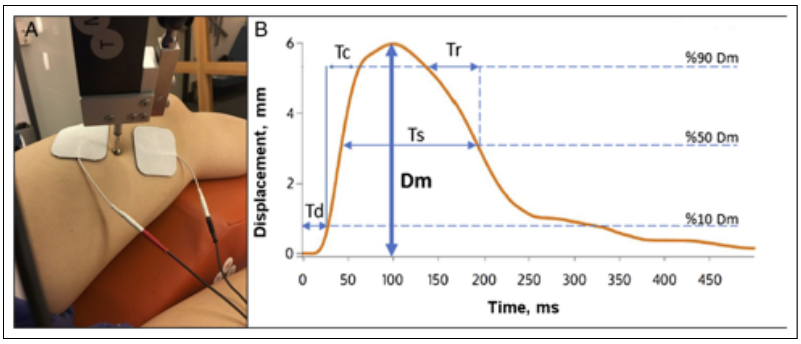

Figure 2.1 (A) The TMG measurement setup and (B) typical TMG parameter definitions. TMG indicates tensiomyography.

2.2.2.2 Kinesio Taping technique. KT Technique. After first TMG measurement, 5 cm width Kinesio tape (Kinesio Tex GoldTM, Albuquerque, NM) was applied on the right leg by a physical therapist who is trained in applying KT (Figure 2.2). Facilitation KT is claimed to increase the muscular activity of the underlying muscle by creating a concentric pulling force on the muscle [36]. To test the occurrence of a muscle facilitatory effect, the KT facilitation technique, that is, taping from muscle origin to insertion, was applied. First, the base of Y-shaped KT was applied on VMO muscle origin with no tension. Subsequently, the knee was brought to 30° flexion and the tails were applied with 30% tension through the insertion of the muscle [86].

Figure 2.2 The KT application technique on VMO. KT indicates kinesio taping; VMO, vastus medialis obliquus.

2.2.3 Experimental Protocol

The TMG measurements were performed in 3 different conditions (Figure 2.3):

(1) before KT application (pre−KT),

(2) 45minutes after KT application (post−KT1) with the tape still in place, and

(3) 1 day after KT application (post−KT2) with the tape still in place.

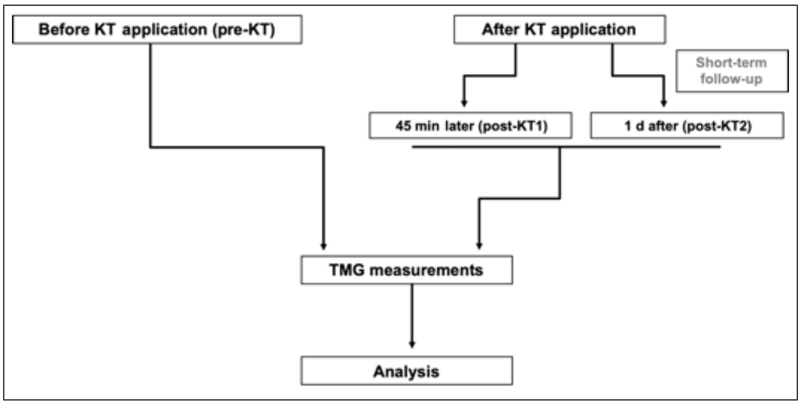

Figure 2.3 Experimental scheme presenting (A) pre-KT, (B) post-KT1, and (C) post-KT2 with the tape still in place. KT indicates Kinesio taping; TMG, tensiomyography.

2.2.4 Statistics

The data were analyzed for normality by using Kolmogorovâ Smirnov test. Due to lack of normal distribution, nonparametric Friedman statistics was used to investigate KT effects on maximal radial displacement and metrics in the time domain. Post hoc Dunn test was applied to locate significant differences across test conditions. All statistical tests were performed in MATLAB R19a (The MathWorks Inc, Natick, MA). Differences were considered significant at $P < .05$. Effect size was determined by Kendall W, $W = \chi 2 / (N [k\text{-}1])$, where $\chi 2$ is the test statistic value output by Friedman test, N is the sample size, and k is the number of measurements per subject (Howell, 2010). Effect sizes were categorized in accordance to Cohen interpretation of W values: of 0.1 (small effect), 0.3 (moderate effect), and above 0.5 (strong effect) [96].

2.3 Results

Significant effects of measurement condition were shown for maximal radial displacement ($P{=}.004$, $W{=}0.50$), contraction time ($P{=}.013$, $W{=}0.40$), relaxation time ($P{=}.035$, $W{=}0.31$), and velocity of contraction ($P = .0033$, $W = 0.52$) (Figures 2.4 and 2.5), but not for delay time ($P{=}.060$, $W{=}0.26$) and sustain time ($P{=}.078$, $W{=}0.23$) (Figure 2.6). Post hoc testing showed (1) a significant decrease in maximal radial displacement for post-KT1 only (from 6.33 [1.46] to 4.87 [2.14] mm) (Figure 4A), (2) a significant increase in contraction time for both post-KT1 and post-KT2 (from 30.87 [11.39] to 39.71 [13.49] ms, and 37.41 [14.73] ms, respectively) (Figure 2.4B), (3) a significant decrease in relaxation time for post-KT2 (from 65.97 [53.43] to 47.45 [38.12] ms) (Figure 2.5A), and (4) a significant decrease in velocity of contraction for both post-KT1 and post-KT2 (from 0.22 [0.08] to 0.15 [0.09] mm/s, and 0.16 [0.07] mm/s, respectively) (Figure 2.5B).

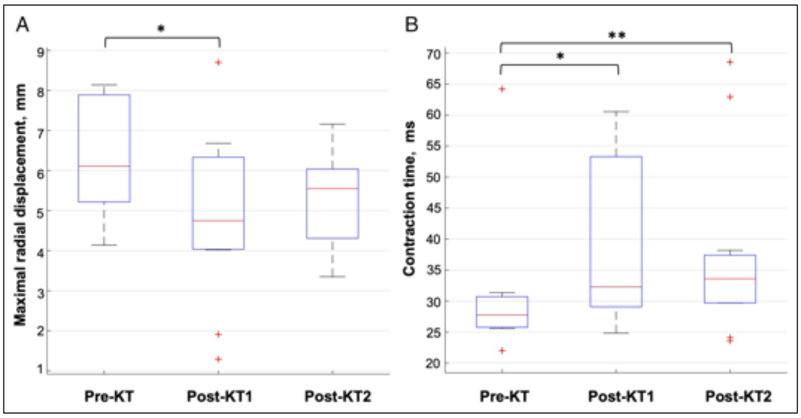

Figure 2.4 Changes in muscle belly maximal (A) radial displacement and (B) contraction time. KT indicates k inesio taping. *Significant changes between pre-KT and post-KT1. **Significant changes between pre-KT and post-KT2.

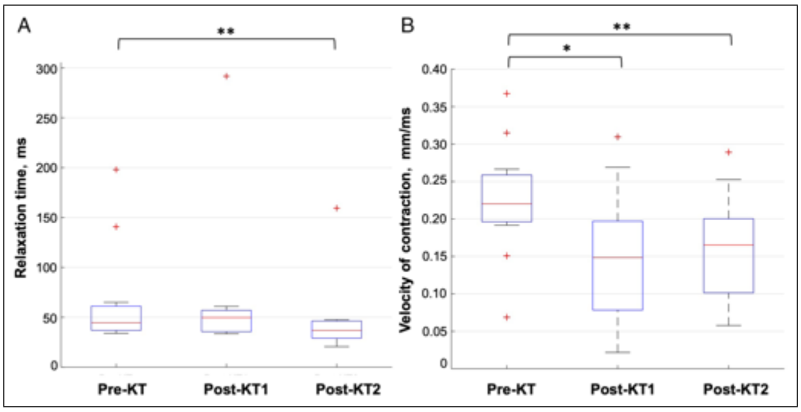

Figure 2.5 Changes in (A) relaxation time and (B) velocity of contraction. KT indicates kinesio taping.

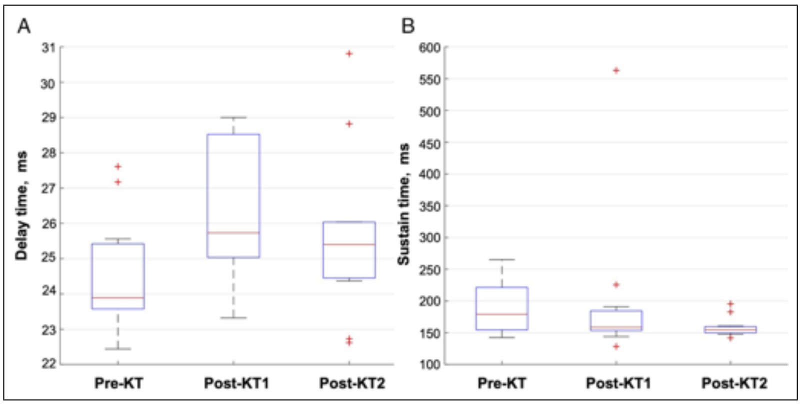

Figure 2.6 Changes in (A) delay time and (B) sustain time. KT indicates kinesio taping.

2.4 Discussion

The results indicate that facilitation KT does have effects on the target muscle's contractile properties, which confirms the hypothesis. Most important effects include a decreased radial displacement (acutely, by 23%), an indicator for increased stiffness and a decreased contraction time characterizing muscle's rate of force development [80] (minimally by 29% both acutely and in the short term).

Note first that, unlike the present findings, many clinicians may tend to expect no effects of KT on muscles of healthy subjects, implicitly assuming that KT will act against a pathology exclusively. For example, a meta-analysis investigating the efficacy of this technique for lower limb muscle strength and functional performance in healthy individuals and those with musculoskeletal conditions indicated that it yielded improved strength only in patients [54]. However, KT leads to externally imposed loading on the tissues, which will not discriminate health or disease to induce effects. In order to elaborate on this issue, the mechanism of KT effects can be considered. First, elastic recoil of KT has been considered to change mechanics of the muscle via actinâmyosin myofilament overlap in sarcomeres and a shift in the length tension curve to lead to an increase or a decrease in muscle tonus [36, 55]. Second, mechanoreceptor responses are accounted for. According to the description of the method, an increase of muscle tonus occurs if KT is applied to impose tension from a muscle's origin to its insertion, which is referred to as the facilitation technique. It is expected that the recoil effect of the tape may enhance muscle spindle reflex, facilitating the muscle's contraction toward an elevated tonus. In contrast, for KT application from a muscle's insertion to its origin, recoil effect of the tape may restrain motor neurons by stretching the Golgi tendon organs at the distal end of the muscle, which is referred to as the inhibition technique [54, 33]. Third, it is considered that continuous stretch and pressure applied by KT on the skin and superficial fascia covering the muscle can stimulate cutaneous mechanoreceptors to sense muscle tension and length changes [97]. Such stimulation activates modulatory mechanisms within the central nervous system resulting in muscle excitability increase [34]. Change in muscle fascicle length is indicated as a determinant for voluntary movement control in the central nervous system [98] which can cause alterations in muscle tone [97]. In a recent study, we have shown detailed KT effects on muscles of healthy individuals in relaxed state [87]. The findings of the present study reflect the mechanisms addressed above as muscle-specific evidence of KT effects on contractile properties of the target muscle and sustain their occurrence in healthy tissue.

A notable finding is the simultaneous increase in muscle stiffness and decrease in rate of force production, acutely. According to functional morphology, twitch time characteristics change with muscle length [99]. The VMO muscle mainly contributes to knee extension and presently, in the testing position, it was at an intermediate length. Therefore, reduced muscle fiber lengths acutely due to the KT facilitation technique applied is tenable. For sarcomeres in the descending limb of their length force curves, this can lead to an increase in a muscle's force production, and shortened muscle spindles would explain the slower muscle response, which is in concert with the increased Tc. In post- KT2, such effect on the muscle fibers is still tenable, but sarcomeres appear to have readjusted their lengths after 1 day, as indicated by the lack of significant change in Dm. This might suggest that regarding muscle's contractile properties, KT is effective when applied and its effects persist for a short time after application. Also, these changes, in accordance with KT's ability to provide an external support to the underlying tissue, show that this particular application has limited the ability of VMO to displace radially upon contraction. Such additional resistance to radial expansion is conceivable to limit the muscle's capability to stretch and do work

[100].

The findings agree with those of Alexander et al [101] which showed an inhibition effect for the lower trapezius muscle although facilitation taping was applied. Reynard et al [102] reported a decrease in the upper trapezius activity in the KT group compared with the sham tape and control groups. The authors explained the decreased muscular activity with an altered proprioceptive feedback and neuromuscular control. On the other hand, velocity of contraction is considered in relation to muscular force changes [68] and is sensitive to fatigue after intensive strength training [75] and also, an increased relaxation time indicates the presence of fatigue [64, 75]. Presently measured drop-in velocity of contraction both for post- KT1 and post-KT2 implies that KT application reduced muscle force production in concert with the increased contraction time and hence suggests that muscle inhibition was manipulated. Note that a lack of an increased relaxation time and therefore no elevated fatigue shown during the testing support this. Although the present study did not investigate KT effects on strength, such inhibition effect may be consistent with the lack of increase in strength in Yam et al[54]. The results of MRI analyses Pamuk and Yucesoy [87] employed can explain why it is not accurate to expect KT to have a unique effect, and only in pathological conditions. Their high- resolution data delivering tissue strains for each 1-mm3 voxel showed that facilitation KT application leads to heterogeneous tissue elongations and compressions at different parts of the muscle both in terms of amplitude and direction. This suggests that a uniform facilitation effect of KT may not be plausible. In contrast, they argued that KT outcome will be a resultant of distributed varying effects ascribed to myofascial force transmission [23, 28] as the underlying mechanism for heterogeneous tissue deformations [103] and altered mechanical behavior of muscles in health [104, 31, 30] and disease [105, 106, 107, 108].

Clinical implications of the present findings are as follows. The targeted VMO muscle is a knee extensor that works as a medial patellar stabilizer. It remains active during knee extension to balance lateral pull from the vastus lateralis and helps keep the patella stable (Lieb Perry, 1971). Patellofemoral syndrome, one of the most common musculoskeletal knee disorders treated in clinical practice, is ascribed to VMO weakness

[109]. The application of facilitation KT clinically aims at increased VMO activity, which can reduce patellofemoral syndrome by correcting impaired patellar position. Increased muscle stiffness shown may provide such patella stabilizing mechanical effect expected from KT. However, lack of a facilitation effect shown presently suggests that KT is effective through a more complex mechanism than clinically expected involving multidirectional local tissue length changes [87]. Lymphatic drainage and effects on free nerve endings are likely to contribute to pain reduction. New studies combining TMG and MRI analyses to assess contractile properties along with high-resolution local tissue effects are indicated for an improved understanding of the mechanism of KT effects.

The limitations of the present study should be considered. First, although studies on healthy individuals are important for our understanding of the mechanism of action of KT, the study includes no pathological conditions. Under such conditions, changes in muscle tone, stiffness, and force development rate are plausible and hence quantified KT effects may be different, which needs to be studied. Second, the targeted VMO is a pennate muscle and as previously shown, muscle length dependent twitch time characteristics are affected by muscle architecture. Pennate muscles have relatively short fibers, and their maximum shortening velocity is expected to be low [99]. Therefore, KT effects on muscles with different or more complex architectures can vary in terms of twitch contraction and relaxation times. Third, the present study focused on KT as a widely used representative of this kind of intervention, but did not address different types of tapes, and varying amounts of tape tension. As addressed above, we consider that taping represents an external mechanical load applied on the skin, effects of which is reflected onto the underlying tissues as myofascial loads. These are plausible effects determined by the mechanical interplay between such load and tissue properties [28], which cannot be considered as limited to the particular tape used presently. Yet, other tapes and applications can lead to variations in the loads imposed and hence different outcomes, which needs to be studied. Finally, the present study reveals that TMG is a promising technique for muscle-specific assessment of contractile properties but the findings lack a direct measurement of muscle stiffness. Although this is difficult to accomplish in vivo, imaging techniques, such as supersonic shear imaging and magnetic resonance elastography, may be used in future studies.

In conclusion, the findings indicate that KT leads to an increased muscle stiffness and a reduced muscle rate of force production. Such lack of a facilitation effect shown despite the facilitation technique applied suggests that KT is effective through a more complex mechanism than clinically expected. Based on our previous studies, this mechanism may involve myofascial force transmission, through which externally imposed loads by the tape can lead to multidirectional local tissue length changes in the target muscle, instead of a homogeneous tissue shortening causing reduced muscle fiber lengths. New studies in patient groups and a combination of TMG and medical imaging techniques are indicated for an improved understanding of the mechanism behind KT effects.

3. KINESIO TAPING EFFECTS ON ALONG-MUSCLE FASCICLE LOCAL LENGTH CHANGES: MAGNETIC RESONANCE AND DIFFUSION TENSOR IMAGING BASED ASSESSMENT

3.1 Introduction

Kinesio taping (KT) is widely applied for the prevention or treatment of joint, ligament, tendon and muscle related injuries, and to improve athletic performance by regulating muscular function [32, 110, 111, 112]. Imposing pressure or stretching on the skin, KT is considered to load the underlying superficial fascia in specific directions and reinforce the function of the fascia [113]. Such fascial system [114] is intrinsically linked to surrounding tissues [115] and is continuous with muscular connective structures such as the epimysium, perimysium and endomysium. Due to myofascial continuity of the epimuscular connective tissues with the extracellular matrix (ECM) [5] loading effects of the superficial tape is distributed through deep muscular fascia indirectly via force transmission [97]. Central to this concept are myofascial loads [28] i.e., forces acting on the muscle belly that are transmitted deep into the muscle via the fascial system. Such myofascial loads can affect mechanical equilibrium locally at different muscle parts. Using magnetic resonance imaging (MRI) based tissue deformation analysis techniques, myofascial loads developed due to joint position changes were shown to cause lengthening and shortening of different parts of lower leg muscle tissues in human, in vivo [116, 117]. In a later study, this mechanism was shown to lead to muscle and connective tissue length changes of differing amplitudes and directions locally in human lower leg after KT application [87]. Those MRI techniques are powerful tools to assess KT effects because they yield a high-resolution local assessment directly in the tissue level instead of a broad whole individual level testing which may be affected marginally by KT or may be affected by also other factors.

Remarkably, KT was shown to increase muscle force [118]. The effects of KT on such muscle force production are to be attributed to its effects on sarcomere lengths [55] as that is the key parameter determining muscle's force production capacity characterized by actin-myosin overlap [11]. Of course, to detect sarcomere length changes in vivo is very difficult. However, combining with diffusion tensor imaging (DTI), the MRI techniques can allow quantifying local length changes along muscle fascicles [31, 30]. Continuous fascial system, whether myofascial loads impose effects in the muscle fascicle level onto the endomysium and perimysium can be tracked via along-muscle fascicle shearing strains [119]. Taking into account multimolecular connections between the extracellular matrix and muscle fibers [120, 121], myofascial loads reaching to such levels can lead to along-muscle fascicle length changes. Mechanical mechanism of this has been studied recently using finite element modeling [122]. Combined MRI based tissue deformation analyses and DTI based fiber tracking comprise an effective technique to study these effects.

We hypothesized that mechanical loading induced on the skin by KT leads to along-muscle fascicle shear and length changes in the targeted muscle. The aim of this study was to test this hypothesis by using combined MRI based deformation analyses and DTI based fiber tracking and reveal such KT effect for the first time.

3.2 Methods

Experimental procedures were in strict agreement with guidelines and regulations concerning human welfare and experimentation set forth by Turkish law, and approved by a Committee of Ethics of Human Experimentation at Boğaziçi University, İstanbul.

Table 3.1
Anthropometric data.

Subject	Age	Weight	Height	BMI.
A	34	54	1.67	19.4
B	32	57	1.6	22.3
C	29	50	1.64	18.6
D	32	61	1.6	23.8
E	31	54	1.63	20.3

3.2.1 Participants

Five healthy female subjects (mean age 32±SD 3 years, height =163±3 cm, body mass = 56±5 kg) volunteered (Table 3.1). Subjects were asymptomatic and had no history of injury in their lower extremities. Volunteers without a history or symptoms of musculoskeletal injury or disease were allowed to proceed. The subjects had been instructed to shave the taping area 24 hours prior to the experiment. After a full explanation of the purpose and methodology, the subjects provided informed consent.

3.2.2 Experimental Protocol

General orthopedic physical therapy assessments (manual muscle tests, flexibility tests and measurement of normal range of motion) for lower limb were done. Subjects were placed on the MRI table in supine position. The right foot was placed in a custom-made MRI-compatible fixation device, ankle was fixed at a 90° angle. The lower leg was supported from the heel and the hamstrings ensuring it was suspended without external contact. Following every intervention, subjects were brought back to this position. To achieve consistency in re-positioning, the metatarsal region was fixed with Velcro and the ankle was fixed at the medial and lateral malleoli. A set of anatomical and diffusion tensor images (DTI) were acquired in 3 conditions: at rest without tape (undeformed state), following a sham tape application, and after KT application.

3.2.3 Kinesio Taping Technique

After the first MRI acquisition, the patient table was moved out. Sham tape application was mimicked in accordance with the KT technique, but no actual tape was adhered. Then, the patient table was automatically moved into the bore to the same isocenter. After the second acquisition, patient table was moved out for the KT application. KT was applied on the right foot by a physical therapist trained in applying KT. 5cm width standard Kinesio tape (Kinesio Tex GoldTM, Kinesio Holding Company, Albuquerque, NM) was applied without removing the subject's foot from the MRI compatible fixation device. The base of I-shaped KT was applied on the insertion of Tibialis Anterior (TA) under zero tension. The rest of the tape was stretched proximally to the upper â of the proximal tibia with maximal tension. The last 4 cm of the tape was applied without any tension on the tibial tuberosity. Subsequently, the ankle was brought to plantar flexion and the tape was adhered over the skin along the TA muscle proximally to distally. This imposes a distally directed load. After waiting for 30 minutes to ensure the tape was fully adhered to the skin, a third MRI acquisition was made.

3.2.4 Anatomical Image and DTI Acquisition

3D turbo fast low-angle shot (Turbo FLASH) sequence was used to acquire high resolution isotropic images for displacement field calculation. 2D single shot echo planar imaging (ss-EPI) with diffusion weighting was used for diffusion tensor calculation and fiber tracking. Imaging study was performed in a 3T MR scanner (Magnetom Prisma fit, Siemens, Erlangen, Germany) using a surface coil and the spine coil for acquisition. See Table 3.2 for a list of imaging parameters of the two modalities.

Table 3.2
Imaging Parameters.

	Anatomical	DTI
Imaging sequence	Turbo FLASH	ss-EPI
Slice orientation	Coronal	Axial
Repetition time (TR) (ms)	1750	4700
Echo time (TE) (ms)	3.36	53
FOV (mm2)	320x320	192x192
Pixel size (mm2)	1.0x1.0	1.5x1.5
Slice thickness (mm)	1	5
Slice spacing (mm)	1	6
Flip angle (Â°)	12	90
Bandwidth (Hz/pixel)	130	2003
b-value (s/mm2)	N/A	450
Number of excitations (NEX)	1	8 for b = 0
		1 for b = 450
Number of diffusion directions	N/A	30
Inversion time (TI) (ms)	1100	N/A

3.2.5 Calculation of In Vivo Local Tissue Deformations

Displacement of the soft tissue between experiment steps was calculated by deformable image registration (DIR). As pre-processing steps, images were trimmed, N4ITK bias field correction was applied to correct for differences in grayscale values due to receiver sensitivity. Then, diffeomorphic B-spline deformation model with mutual information similarity metric was applied. An open source DIR toolkit, elastix was used [123]. This technique utilizes the contrast in the grayscale values to find the minima of the similarity metric, where two images maximally overlap. When registration converges, a displacement vector for each voxel is obtained, i.e., a displacement field. Green-Lagrange strain tensor field was algebraically derived from the displacement field. Along-muscle fascicle length changes and shear strains were calculated from the strain tensor field as described in previous MRI and DTI study [30].

3.2.6 Determination of Muscle Fascicle Directions

Joint Rician noise filtering was applied to the DTI for fiber tracking reliability. Subsequently, diffusion tensors were estimated for each voxel. Fiber tracking was performed with distal aponeurosis as the seed points. Tracking was continued in 0.75 mm steps as long as: Fractional Anisotropy (FA) $>$ 0.15, curvature $<$ 0.7-1mm. Fibers were filtered with the criteria: 20 mm $<$ length $<$ 200 mm [84]. Tracked fibers crossing the delineated boundaries of the TA were eliminated.

3.2.7 Testing of MRI Repeatability

Potential effects of the experimental design, MRI, and algorithmic artifacts were the sources of variation between the initial and the sham application acquisition conditions. Detected deformation and tracked fiber variation demonstrated the baseline error for this study.

3.2.8 Statistics

Non-parametric Wilcoxon signed-rank tests were performed for differences between in vivo muscle fiber lengthening and shortening due to sham application vs. KT application. 100 nodes were selected randomly from the tracked fibers in each condition. $P < 0.05$ was considered significant.

3.3 Results

Data pooled from all subjects show that along-muscle fascicle shear strains and along-muscle fascicle length changes due to KT application were significantly larger than their counterparts due to the sham application (Table 3.3).

Table 3.3
Comparison of in vivo strains on the TA due to sham vs. KT application.

Sham application	mean ± SD
Fiber lengthening	0.012 ± 0.010
Fiber shortening	-0.013 ± 0.015
Fiber shearing	0.029 ± 0.021
Kinesio tape application	
Fiber lengthening	0.026 ± 0.020*
Fiber shortening	-0.032 ± 0.027*
Fiber shearing	0.087 ± 0.049*

3.3.1 Along-muscle fascicle shear strains

Along-muscle fascicle shear strains visualized per subject (Figure 3.1) confirm the presence of shearing between fascicles. Peak shear strain amplitudes vary across subjects (maximally 0.25 for subject A and minimally 0.10 for subject C).

3.3.2 Along-muscle fascicle length changes

Figure 3.2 does indicate that KT caused a heterogeneous distribution of along-muscle fascicle length changes for all subjects, which includes both lengthening and shortening occurring along the same fascicles locally at different fascicle parts. A general pattern of lengthening in distal fascicle parts (all subjects, up to 6, 6, 5, 12 and 9% for subjects A to E, respectively) and shortening in proximal fascicle parts (except subject C, up to 6, 5, 9 and 14% for subjects A, B, D and E, respectively) were observed. However, in addition to differences in strain amplitudes among different subjects, exceptions to the general pattern do exist: (i) distal-most fascicle parts show varying amounts of shortening (subjects A, C, D and E, up to 11, 3, 1 and 6%, respectively). (ii) For subject C, also proximal fascicle parts show lengthening (up to 6%) whereas middle fascicle parts show shortening (up to 7%).

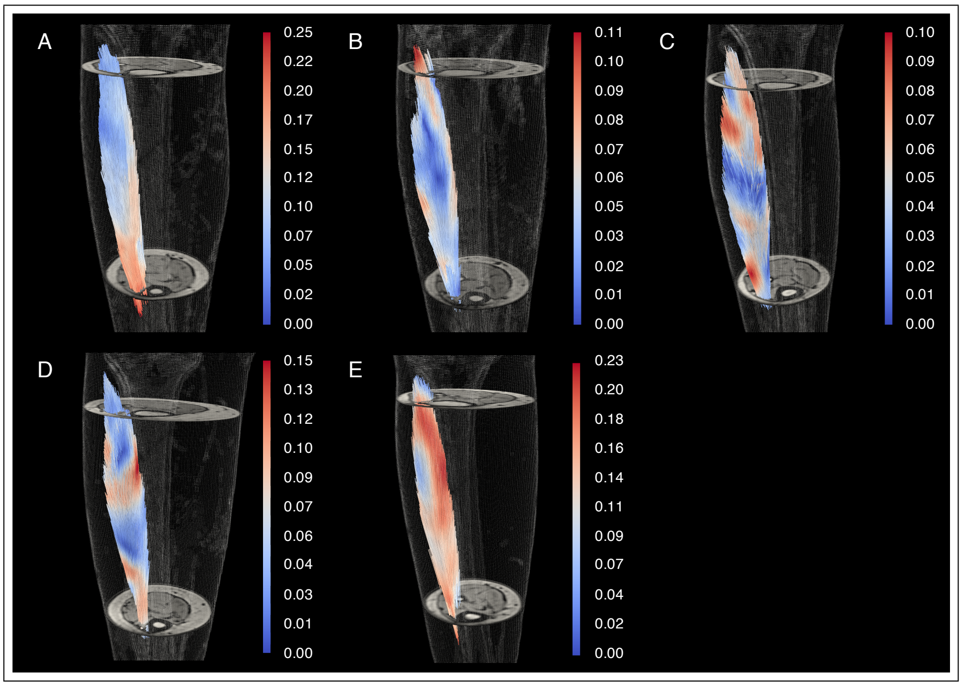

Figure 3.1 Along-fiber shear strain distributions of subjects A-E. Along fiber shear strains are displayed on tracked fibers of the TA. Two axial slices at the extreme ends of the tracked fibers and the volume silhouette are shown for reference. Colormaps reflect the full range of values for each individual separately.

3.4 Discussion

The main objective of the present study was to quantify local length changes along-muscle fascicles after KT application by combining MRI-based deformation and DTI-based fiber tracking analyses. To the best of our knowledge, this is the first study which reports local shear strains and length changes occurring along muscle fascicles in human muscle due to KT application in vivo. The findings reveal that KT induced mechanical loading resulted in along-muscle fascicle shear strains and length changes locally in varying amplitudes in the TA. Therefore, our hypothesis is confirmed. These data challenge the simplifying assumptions made to understand the effect of KT application mechanically in the fascicle level and motivated us to identify effect mechanism of KT that could contribute to nonuniform shear strains and length changes.

In mechanics, if a component of force acts normal to the surface of a structure, a tensile or compressive stress is created depending on the direction of the force com-

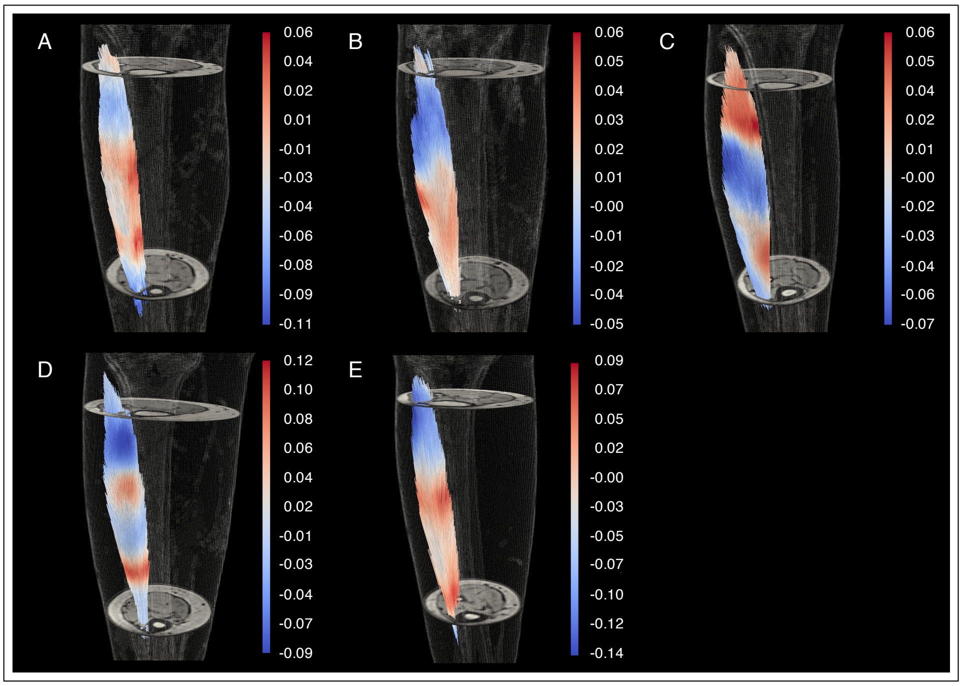

Figure 3.2 Fiber length change distributions of subjects A-E. Fiber length changes are displayed on tracked fibers of the TA. Two axial slices at the extreme ends of the tracked fibers and the volume silhouette are shown for reference. Lengthening is represented in red hues, shortening is represented in blue hues. Colormaps reflect the full range of values for each individual separately.

ponent and as a result, length changes along the material are observed [124]. On the other hand, if a force component acts in plane with the surface, a shear stress is generated causing a twisting and/or a shearing deformation [124]. Therefore, for muscle tissue, forces acting on its belly will have both types of components that can locally lead to length changes (normal components) and orthogonality changes (shear components). For example, forces along muscle line of action can yield changes to length of the muscle locally [92]. Of course, function vise interesting orientation to consider the effects of such forces is along-muscle fascicle direction because sarcomeres are arranged along muscle fibers which form muscle fascicles. In the present study, both along-muscle fascicle length changes and shear strains were observed, which indicates that KT imposed forces on the target muscle cause effects locally in such functionally interesting orientation. Such forces have been referred earlier to as myofascial loads [122, 28]. Previous mathematical modeling studies showed that myofascial loads bared in the extracellular matrix domain can manipulate local length changes in the muscle fiber direction [122, 29, 125] and hence can impose mechanical effects onto the muscle fiber domain [103, 126]. Myofascial force transmission mechanism for that has been described by Huijing [121] ascribed to multimolecular protein structures linking these two domains [120] and central to that a shearing type of mechanical interaction was indicated to occur between the muscle fibers and the endomysium [119, 127, 128]. Consequently, along-muscle fascicle shear strains were studied presently as an objective indicator to show the presence of such myofascial force transmission as an effect of KT application. Local heterogeneity of along-muscle fascicle shear strains shown indicates that mechanical loads imposed by KT superficially on the skin are spread inhomogeneously into deeper structures including the target muscle via epimuscular myofascial force transmission. Such inhomogeneous spread of loads is ascribable to inhomogeneous content and stiffness of collagenous structures interlinking skin to the muscle and they imply that both direction and amplitude vise myofascial loads must be variable. A consequence of that is locally varying along muscle fascicle strains observed involving both lengthening and shortening occurring along the same muscle fascicle in different parts. In terms of the above described mechanism, these results are in concert with our previous findings, which showed non-uniform and heterogenous local tissue lengthening and shortening occurring in different amplitudes and directions due to KT application [87]. However, presently we show for the first time that those effects may affect sarcomere lengths hence muscular force and movement production.

Sarcomere is the basic functional unit of muscle fiber and its length is the main parameter affecting muscular force production [11, 129]. Variation in muscle fiber and fascicle length change cause a significant spatial variations in muscle force [130]. Elastic recoil of KT has been considered to change sarcomere length yielding a shift in the length tension curve [55] and increase in muscle force [118]. However, such KT effects locally along-muscle fascicles have not been shown. Our present results reveal that KT application causes a heterogeneous distribution of lengthening and shortening to occur locally along-muscle fascicles for all subjects. Previously, it was shown experimentally in an intact muscle compartment that after distally lengthening a muscle while keeping its proximal tendon at constant position, substantial force differences were measured at both ends of the muscle and a matching mathematical modeling work indicated a heterogenous muscle fiber direction strain distribution i.e., a serial distribution of sarcomeres [29]. The model also explained that this affects the force production in the proximal and distal parts of the muscle in concert with the experimentally measured proximo-distal force differences. Moreover, an increased heterogeneity of mean fiber sarcomere lengths across different muscle fascicles were shown i.e., a parallel distribution [131], which caused the shift in muscle's optimum length to a longer muscle length measured experimentally [29]. Other studies also revealed similar effects of myofascial loads originating from muscle relative position changes [31, 30], surgery [132, 133, 29] or chemical denervation [134, 107, 135] on muscle's force and movement production. The importance of the present study is that KT effects were shown to translate into such myofascial loads yielding heterogeneity of local lengthening and shortening along muscle fascicles. Although the present experiments were conducted in the passive state, these findings suggest strongly that KT can manipulate muscle force development mechanism and lead in the active state to effects on joint moment and movement. Noting that muscle activation will essentially cause sarcomere shortening, it is tenable that the presently shown local shortening along muscle fascicles may elevate and local lengthening may diminish. However, such distribution of local length changes is unlikely to vanish in the active state. In a KT free experiment, a similar effect of active state testing was shown for the medial gastrocnemius muscle in isometric condition to manipulate along muscle fascicle strains calculated in passive state imposed by bringing the knee from flexion to extension [30]. After muscular strain, clinical bed rest, post-surgeries or spaceflights a key rehabilitation goal is reducing muscle atrophy and protecting physiological range of motion by preventing muscle fascicle length changes [16, 136, 17]. Based on the present findings, the use of KT should be considered as a supportive/manipulative tool to tailor muscle's contribution to joint force and range of motion during the course of such treatment.

The present study has some limitations that need to be acknowledged. Firstly, the study was performed in passive condition and did not monitor muscle activity. However, this was done in our previous works using EMG and relaxed state of the subject during experiment was shown [116, 117]. Although, quantification of the effects of KT on along muscle fascicle length changes in active state is lacking, taking into account previous active state experiments [31], possible changes to our results are discussed above. Secondly, the study was conducted in only healthy individuals.

Under pathological conditions, changes in muscle architecture and tissue properties are plausible [137, 17] and hence the quantified KT effects may be different and this should be studied. However, the present study does indicate occurrence of variable KT effects locally in healthy tissue, which may be considered as unlikely [54]. Similarly, KT effects globally on healthy muscle and in active state were reported recently [138]. Thirdly, TA is a pennate fibered muscle. As muscle architecture affects muscle fiber reaction to mechanical pressure and electrical stimulus [99], current findings should not be generalized without additional investigation on different muscle architectures. Also, in the active state muscle pennation angle is known to change implying that KT effects on even the same muscle may change. Yet, it is very unlikely that the effects of KT as externally imposed loads translated into myofascial loads manipulating local length changes along muscle fascicles will vanish. Lastly, only very acute effects of KT were investigated in this study indicating the need to evaluate how such effects may change in the course of treatment.

In conclusion, the present findings show that KT has effects on skeletal muscle mechanics. These effects include along-muscle fascicle length and direction change locally and can be measured by using MRI and DTI combination.

4. GENERAL DISCUSSION

Major findings of the current studies reveal that (i) KT affects muscle contractile properties such as stiffness and rate of force production, (ii) KT leads to along-muscle fascicle shear and length changes. KT-imposed pressure or stretching on the skin causes a loading effect on superficial fascia in specific directions. Due to linkage of fascial system with surrounding tissues such as epimysium, perimysium and endomysium, these loading effects of superficial tape is distributed through deep muscular fascia indirectly via force transmission.

According to the result of TMG study, KT was shown to increase muscular stiffness. Myofascial loads imposed by KT on superficial fascia were distributed to deeper connective muscular layers lead to length changes along-muscle fascicles as shown in MRI and DTI experiment. Due to muscle volume constancy, altered muscle fascicle length is in concert with change in stiffness [92]. Increased stiffness might be also related to relative change in heterogeneity of parallel distribution of sarcomeres, which might lead to a shift in length tension curve and a difference in force production capacity [131]. Altered time-based metrics of TMG correlated to contraction velocity of a muscle might be attributed to recoil effect of KT on serially distributed sarcomeres which in turn related to force excursion of a muscle by extending muscle length range [13]. Therefore, KT imposed myofascial loads change muscle stiffness by causing a heterogeneity in sarcomere distribution both serially and paralelly via force transmission.

Heterogenous along-muscle fascicle length change shown in MRI and DTI experiment due to KT confirm earlier findings that myofascial loads are major cause for such heterogeneity in along-muscle fascicle length [28]. KT-imposed myofascial loads affected mechanical equilibrium of different parts of muscle fascicle both in terms of shortening and lengthening by epimuscular myofascial force transmission. It is tenable that these length changes in fascicles due to KT can cause altered muscle force production capacity in affected part of the muscle by leading a shift in force length graph.

In another MRI based DTI study in which sarcomere heterogeneity was shown, shortening part of the muscle fascicle were considered as stretched while lengthening muscle fascicle parts was considered as activated [31]. Therefore, lengthening part of muscle fascicles due to KT are likely to produce more force than shortening fascicle parts. This result verifies the study that KT application on biceps brachii improved the elbow peak torque by increasing muscular activation [45]. In another meta analyze, although effects of KT were restricted with pathological cases, KT was found to be superior in terms of improving lower limb muscle force in post-op situations or musculoskeletal diseases [54]. Moreover, as joint movement and ROM directly relate to muscle action, the change in muscle force due to KT is likely to provide an improvement in joint ROM. In a study investigating the effects of KT on pain , physical function and ROM, KT was shown to improve ROM [41]. In pathological cases such as osteoarthritis or total knee replacements, KT was found to have beneficial effects on active range of motion, gait and function of the patients [58, 59]. The effects of KT on motion and movement can be attributed to its effects on along-muscle fascicle length change, hence force production as shown in MRI and DTI study. By altering muscle force production capacity, KT was also found to be effective on countermovement jumping performance of male athletes [60]. Therefore, altered fascicle length in different part of muscle in terms of lengthening and shortening due to KT might change inter-sarcomere dynamics and lead to muscular force change. As a result range of motion, gait, jumping performance and functional parameters can be improved.

With respect to the effects of KT on along-muscle fascicle and hence on sarcomere length, muscle force changes due to KT application is attributed to its effects on muscle spindle and Golgi Tendon Organ (GTO). It is considered that when KT is applied from muscle origin to insertion, the recoil effect of the tape stimulate length change sensitive muscle spindles and hence activation of muscle spindle improves muscle force. In reverse situation, if tape is applied from insertion to origin of the muscle, it is considered to activate stretch sensitive GTO and causes an inhition effect on the muscle [54, 33]. Therefore, the change in along muscle fascicle length shown by MRI and DTI experiment and stiffness shown by TMG experiment might reveal that KT both changes relative muscle length and tension, hence might activate both muscle spindle and GTO. Consequently, KT might stimulate muscle spindles or GTO by causing alterations in along-muscle fascicle length and might inhibit or facilitate muscle contraction.

Due to continuity of deep fascia with ECM, fascial tissue have ability to adapt and respond to muscle stretch and contraction. Therefore, it has an important role in musculoskeletal health. After musculoskeletal injuries or traumas, sliding of superficial fascia might be restricted and elasticity of facial system reduces. Lack of mobility or sliding in collagen fibers, fascia becomes stiffer and adhesive which might cause a reduction in mechanical interaction between ECM layers and muscle tissue. Moreover, increased stiffness of endomysium and perimysium might diminish global tensional network of fascia and can cause a lack of force transmission [139, 18]. Therefore, as a myofascial load on superficial fascia, KT application might reduce adhesion of the superficial fascia and improve mobility of soft tissues. Therefore, KT can increase the quality of movement and ROM by improving connective tissue mobility. Additionally, KT was found to be effective not only on targeted tissues, but also on non targeted tissues [87]. Therefore, KT should be used as a supportive technique to manual treatments to reduce both underlying and neighboring fascial problems and improve fascial organization as well as force transmission.

In conclusion, KT has major mechanical effects on skeletal muscle mechanics. These effects contain significant changes in stiffness, rate of force production, along-muscle fascicle length and shear strain changes. Due to mechanical interaction between tape and fascia; and fascia with deeper connective muscular structures, superficial effects of KT are transmitted into inner structures and affect distribution of sarcomeres in serial and parallel, hence force production.

REFERENCES

1. Mukund, K., and S. Subramaniam, "Skeletal muscle: A review of molecular structure and function, in health and disease," *Wiley interdisciplinary reviews. Systems biology and medicine*, Vol. 12, Jan. 2020. Publisher: Wiley Interdiscip Rev Syst Biol Med.

2. Lieber, R. L., and J. Fridèn, "Functional and clinical significance of skeletal muscle architecture," *Muscle Nerve*, Vol. 23, pp. 1647–1666, Nov. 2000.

3. Schmalbruch, H., *Skeletal Muscle*, Springer Science & Business Media, Dec. 2012.

4. Nishimura, T., A. Hattori, and K. Takahashi, "Ultrastructure of the intramuscular connective tissue in bovine skeletal muscle. A demonstration using the cell-maceration/scanning electron microscope method - PubMed," 1994.

5. Huijing, P. A., "Epimuscular myofascial force transmission: a historical review and implications for new research. International Society of Biomechanics Muybridge Award Lecture, Taipei, 2007," *J Biomech*, Vol. 42, pp. 9–21, Jan. 2009.

6. Lieber, R. L., *Skeletal Muscle Structure, Function, and Plasticity*, Lippincott Williams & Wilkins, 2002. Google-Books-ID: T0fbq_b89cAC.

7. Mense, S., D. G. Simons, and I. J. Russell, *Muscle Pain: Understanding Its Nature, Diagnosis, and Treatment*, Lippincott Williams & Wilkins, Jan. 2001.

8. Wang, K., J. McClure, and A. Tu, "Titin: major myofibrillar components of striated muscle," *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 76, Aug. 1979. Publisher: Proc Natl Acad Sci U S A.

9. Richifield, D., "Medical gallery of David Richifield," *WikiJournal of Medicine*, Vol. 1, no. 2, 2014.

10. Pham, S., and Y. Puckett, *Physiology, Skeletal Muscle Contraction*, StatPearls Publishing, May 2022. Publication Title: StatPearls [Internet].

11. Gordon, A. M., A. F. Huxley, and F. J. Julian, "The variation in isometric tension with sarcomere length in vertebrate muscle fibres," *J Physiol*, Vol. 184, pp. 170–192, May 1966.

12. Gans, C., and A. S. Gaunt, "Muscle architecture in relation to function," *J Biomech*, Vol. 24 Suppl 1, pp. 53–65, 1991.

13. Wohlfart, B., A. F. Grimm, and K. A. Edman, "Relationship between sarcomere length and active force in rabbit papillary muscle," *Acta physiologica Scandinavica*, Vol. 101, Oct. 1977. Publisher: Acta Physiol Scand.

14. Narici, M. V., T. Binzoni, E. Hiltbrand, J. Fasel, F. Terrier, and P. Cerretelli, "In vivo human gastrocnemius architecture with changing joint angle at rest and during graded isometric contraction.," *The Journal of Physiology*, Vol. 496, p. 287, Oct. 1996. Publisher: Wiley-Blackwell.

15. Chapman, I., C. MacIntosh, J. Morley, and M. Horowitz, "The anorexia of ageing," *Biogerontology*, Vol. 3, no. 1-2, 2002. Publisher: Biogerontology.

16. Koryak, Y. A., "Changes in human skeletal muscle architecture and function induced by extended spaceflight," *Journal of Biomechanics*, Vol. 97, p. 109408, Dec. 2019.

17. Sinha, U., R. Csapo, V. Malis, Y. Xue, and S. Sinha, "Age-related differences in diffusion tensor indices and fiber architecture in the medial and lateral gastrocnemius," *Journal of magnetic resonance imaging : JMRI*, Vol. 41, Apr. 2015. Publisher: J Magn Reson Imaging.

18. Schleip, R., A. Zorn, and W. Klingler, "Biomechanical Properties of Fascial Tissues and Their Role as Pain Generators," *Journal of Musculoskeletal Pain*, Vol. 18, pp. 393–395, Oct. 2010. Publisher: Taylor & Francis _eprint: https://doi.org/10.3109/10582452.2010.502628.

19. Wilke, J., V. Macchi, R. De Caro, and C. Stecco, "Fascia thickness, aging and flexibility: is there an association?," *J Anat*, Vol. 234, pp. 43–49, Jan. 2019.

20. Stecco, A., R. Stern, I. Fantoni, R. De Caro, and C. Stecco, "Fascial Disorders: Implications for Treatment," *PM & R : the journal of injury, function, and rehabilitation*, Vol. 8, Feb. 2016. Publisher: PM R.

21. Gatt, A., S. Agarwal, and P. M. Zito, "Anatomy, Fascia Layers," in *StatPearls*, Treasure Island (FL): StatPearls Publishing, 2022.

22. Findley, T., H. Chaudhry, and S. Dhar, "Transmission of muscle force to fascia during exercise," *J Bodyw Mov Ther*, Vol. 19, pp. 119–123, Jan. 2015.

23. Wilke, J., R. Schleip, C. A. Yucesoy, and W. Banzer, "Not merely a protective packing organ? A review of fascia and its force transmission capacity," *J Appl Physiol (1985)*, Vol. 124, pp. 234–244, Jan. 2018.

24. Tidball, J. G., "Force transmission across muscle cell membranes," *J Biomech*, Vol. 24 Suppl 1, pp. 43–52, 1991.

25. Maas, H., and T. G. Sandercock, "Are skeletal muscles independent actuators? Force transmission from soleus muscle in the cat," *Journal of applied physiology (Bethesda, Md. : 1985)*, Vol. 104, June 2008. Publisher: J Appl Physiol (1985).

26. Purslow, P. P., "Muscle fascia and force transmission," *J Bodyw Mov Ther*, Vol. 14, pp. 411–417, Oct. 2010.

27. Yucesoy, C. A., G. C. Baan, B. H. Koopman, H. J. Grootenboer, and P. A. Huijing, "Pre-strained epimuscular connections cause muscular myofascial force transmission to affect properties of synergistic EHL and EDL muscles of the rat," *Journal of biomechanical engineering*, Vol. 127, pp. 819–828, Oct. 2005. Publisher: J Biomech Eng.

28. Yucesoy, C. A., "Epimuscular myofascial force transmission implies novel principles for muscular mechanics," *Exerc Sport Sci Rev*, Vol. 38, pp. 128–134, July 2010.

29. Yucesoy, C. A., B. H. Koopman, G. C. Baan, H. J. Grootenboer, and P. A. Huijing, "Effects of inter- and extramuscular myofascial force transmission on adjacent synergistic muscles: assessment by experiments and finite-element modeling," *J Biomech*, Vol. 36, pp. 1797–1811, Dec. 2003.

30. Pamuk, U., A. Karakuzu, C. Ozturk, B. Acar, and C. A. Yucesoy, "Combined magnetic resonance and diffusion tensor imaging analyses provide a powerful tool for in vivo assessment of deformation along human muscle fibers," *J Mech Behav Biomed Mater*, Vol. 63, pp. 207–219, 2016.

31. Karakuzu, A., U. Pamuk, C. Ozturk, B. Acar, and C. A. Yucesoy, “Magnetic resonance and diffusion tensor imaging analyses indicate heterogeneous strains along human medial gastrocnemius fascicles caused by submaximal plantar-flexion activity,” *J Biomech*, Vol. 57, pp. 69–78, 2017.

32. Bassett, K., S. Lingman, and R. Ellis, “The use and treatment efficacy of kinaesthetic Taping for musculoskeletal conditions: A systematic review,” *N. Z. J. Physiother*, no. 38, pp. 56–62, 2010.

33. Yeung, S. S., and E. W. Yeung, “Acute Effects of Kinesio Taping on Knee Extensor Peak Torque and Stretch Reflex in Healthy Adults,” *Medicine (Baltimore)*, Vol. 95, p. e2615, Jan. 2016.

34. Yoshida, A., and L. Kahanov, “The effect of kinesio taping on lower trunk range of motions,” *Res Sports Med*, Vol. 15, pp. 103–112, June 2007.

35. Halseth, T., J. W. McChesney, M. Debeliso, R. Vaughn, and J. Lien, “The effects of kinesio taping on proprioception at the ankle,” *J Sports Sci Med*, Vol. 3, pp. 1–7, Mar. 2004.

36. Kase, K., J. Wallis, and T. Kase, *Clinical therapeutic applications of the Kinesio taping method. [Albuquerque, NM]: Kinesio Taping Association International.*, 2013.

37. Yu, B., Q. Qi, W. Chen, R. Wang, W. Zhou, and K. Li, “Different application pattern of Kinesio taping on altering its retraction force and subcutaneous space of healthy adults. . Med.,” *Chin. J. Rehabil*, Vol. 31, pp. 296–300, 2016.

38. Zhang, X.-F., L. Liu, B.-B. Wang, X. Liu, and P. Li, “Evidence for kinesio taping in management of myofascial pain syndrome: a systematic review and meta-analysis,” *Clin Rehabil*, Vol. 33, pp. 865–874, May 2019.

39. Taradaj, J., T. Halski, M. Zdunczyk, J. Rajfur, M. Pasternok, D. Chmielewska, M. Piecha, K. Kwaśna, and V. Skrzypulec-Plinta, “Evaluation of the effectiveness of kinesio taping application in a patient with secondary lymphedema in breast cancer: a case report,” *Prz Menopauzalny*, Vol. 13, pp. 73–77, Mar. 2014.

40. Karwacińska, J., W. Kiebzak, B. Stepanek-Finda, I. M. Kowalski, H. Protasiewicz-Fałdowska, R. Trybulski, and M. Starczyńska, “Effectiveness of Kinesio Taping on hypertrophic scars, keloids and scar contractures,” *Polish Annals of Medicine*, Vol. 19, pp. 50–57, Jan. 2012.

41. Abolhasani, M., F. Halabchi, R. Honarpishe, J. A. Cleland, and A. Hakakzadeh, “Effects of kinesiotape on pain, range of motion, and functional status in patients with osteoarthritis: a randomized controlled trial,” *J Exerc Rehabil*, Vol. 15, pp. 603–609, Aug. 2019.

42. Harput, G., H. Guney, U. Toprak, F. Colakoglu, and G. Baltaci, “Acute effects of scapular Kinesio Taping on shoulder rotator strength, ROM and acromiohumeral distance in asymptomatic overhead athletes,” *J Sports Med Phys Fitness*, Vol. 57, pp. 1479–1485, Nov. 2017.

43. Saltan, A., G. Baltaci, and H. Ankarali, “Does Kinesio taping improve balance and functional performance in older adults? A pilot study,” *J Sports Med Phys Fitness*, Vol. 59, pp. 1346–1352, Aug. 2019.

44. Bischoff, L., C. Babisch, J. Babisch, F. Layher, K. Sander, G. Matziolis, S. Pietsch, and E. Röhner, "Effects on proprioception by Kinesio taping of the knee after anterior cruciate ligament rupture," 2018. Library Catalog: www.meta.org.

45. Fratocchi, G., F. D. Mattia, R. Rossi, M. Mangone, V. Santilli, and M. Paoloni, "Influence of Kinesio Taping applied over biceps brachii on isokinetic elbow peak torque. A placebo controlled study in a population of young healthy subjects," May 2013. ISSN: 1878-1861 Issue: 3 Publisher: J Sci Med Sport Volume: 16.

46. Gusella, A., M. Bettuolo, F. Contiero, and G. Volpe, "Kinesiologic taping and muscular activity: a myofascial hypothesis and a randomised, blinded trial on healthy individuals," *Journal of Bodywork and Movement Therapies*, Vol. 18, pp. 405–411, July 2014.

47. Shim, J.-Y., H.-R. Lee, and D.-C. Lee, "The use of elastic adhesive tape to promote lymphatic flow in the rabbit hind leg," *Yonsei Med J*, Vol. 44, pp. 1045–1052, Dec. 2003.

48. Kocyigit, F., M. Acar, M. B. Turkmen, T. Kose, N. Guldane, and E. Kuyucu, "Kinesio taping or just taping in shoulder subacromial impingement syndrome? A randomized, double-blind, placebo-controlled trial," *Physiother Theory Pract*, Vol. 32, pp. 501–508, Oct. 2016.

49. Cameron, M., *Physical Agents in Rehabilitation: From Research to Practice*, WB Saunders, Philadelphia, Pa, USA, 1999.

50. Wu, W.-T., C.-Z. Hong, and L.-W. Chou, "The Kinesio Taping Method for Myofascial Pain Control," *Evidence-Based Complementary and Alternative Medicine*, June 2015. ISSN: 1741-427X Pages: 1–9 Publisher: Hindawi Volume: 2015.

51. Konishi, Y., "Tactile stimulation with Kinesiology tape alleviates muscle weakness attributable to attenuation of Ia afferents," *Journal of Science and Medicine in Sport*, Vol. 16, pp. 45–48, Jan. 2013.

52. Chang, W.-D., F.-C. Chen, K. C.-L. Lee, H.-Y. Lin, and P.-T. Lai, "Effects of Kinesio Taping versus McConnell Taping for Patellofemoral Pain Syndrome: A Systematic Review and Meta-Analysis," *Evid Based Complement Alternat Med*, Vol. 2015, p. 471208, 2015.

53. Lim, E., and M. Tay, "Kinesio taping in musculoskeletal pain and disability that lasts for more than 4 weeks: is it time to peel off the tape and throw it out with the sweat? A systematic review with meta-analysis focused on pain and also methods of tape application," *Br J Sports Med*, Vol. 49, pp. 1558–1566, Dec. 2015.

54. Yam, M., Z. Yang, B. Zee, and K. Chong, "Effects of Kinesio tape on lower limb muscle strength, hop test, and vertical jump performances: a meta-analysis," *BMC Musculoskelet Disord*, Vol. 20, p. 212, May 2019.

55. Morrissey, D., "Proprioceptive shoulder taping," *Journal of Bodywork and Movement Therapies*, Vol. 4, pp. 189–194, July 2000. Publisher: Elsevier.

56. Aydoğdu, O., Z. Sarı, S. Yurdalan, and M. Polat, "Clinical outcomes of kinesio taping applied in patients with knee osteoarthritis: A randomized controlled trial," *J Back Musculoskelet Rehabil*, Vol. 30, pp. 1045–1051, Sept. 2017.

57. Kaya Mutlu, E., R. Mustafaoglu, T. Birinci, and A. Razak Ozdincler, "Does Kinesio Taping of the Knee Improve Pain and Functionality in Patients with Knee Osteoarthritis?: A Randomized Controlled Clinical Trial," *Am J Phys Med Rehabil*, Vol. 96, pp. 25–33, Jan. 2017.

58. Donec, V., and A. Kriščiūnas, "The effectiveness of Kinesio Taping after total knee replacement in early postoperative rehabilitation period. A randomized controlled trial," *Eur J Phys Rehabil Med*, Vol. 50, pp. 363–371, Aug. 2014.

59. Kakar, R., H. Greenberger, and P. McKeon, "Efficacy of Kinesio Taping and McConnell Taping Techniques in the Management of Anterior Knee Pain," *J Sport Rehabil*, Vol. 29, pp. 79–86, Jan. 2020.

60. Mendez-Rebolledo, G., R. Ramirez-Campillo, E. Guzman-Muñoz, V. Gatica-Rojas, A. Dabanch-Santis, and F. Diaz-Valenzuela, "Short-Term Effects of Kinesio Taping on Muscle Recruitment Order During a Vertical Jump: A Pilot Study," *J Sport Rehabil*, Vol. 27, pp. 319–326, July 2018.

61. Pišot, R., M. V. Narici, B. Šimunič, M. De Boer, O. Seynnes, M. Jurdana, G. Biolo, and I. B. Mekjavič, "Whole muscle contractile parameters and thickness loss during 35-day bed rest," *Eur. J. Appl. Physiol.*, Vol. 104, pp. 409–414, Sept. 2008.

62. Simunič, B., "Between-day reliability of a method for non-invasive estimation of muscle composition," *J Electromyogr Kinesiol*, Vol. 22, pp. 527–530, Aug. 2012.

63. Hunter, A., S. Galloway, I. Smith, J. Tallent, M. Ditroilo, M. Fairweather, and G. Howatson, "Assessment of eccentric exercise-induced muscle damage of the elbow flexors by tensiomyography," *J Electromyogr Kinesiol*, Vol. 22, pp. 334–341, June 2012.

64. García-Manso, J. M., D. Rodríguez-Ruiz, D. Rodríguez-Matoso, Y. de Saa, S. Sarmiento, and M. Quiroga, "Assessment of muscle fatigue after an ultra-endurance triathlon using tensiomyography (TMG)," *J Sports Sci*, Vol. 29, pp. 619–625, Mar. 2011.

65. Dahmane, R., S. Djordjevic, B. Simunic, and V. Valencic, "Spatial fiber type distribution in normal human muscle Histochemical and tensiomyographical evaluation," *J Biomech*, Vol. 38, pp. 2451–2459, Dec. 2005.

66. Rusu, L., G. Cosma, S. Cernaianu, M. Marin, P. Rusu, D. Ciocănescu, and F. R. Neferu, "Tensiomyography method used for neuromuscular assessment of muscle training," *Journal of NeuroEngineering and Rehabilitation*, Vol. 10, p. 67, July 2013.

67. Dahmane, R., V. Valen i, N. Knez, and I. Eren, "Evaluation of the ability to make non-invasive estimation of muscle contractile properties on the basis of the muscle belly response," *Med Biol Eng Comput*, Vol. 39, pp. 51–55, Jan. 2001.

68. de Paula Simola, R. A., N. Harms, C. Raeder, M. Kellmann, T. Meyer, M. Pfeiffer, and A. Ferrauti, "Assessment of neuromuscular function after different strength training protocols using tensiomyography," *J Strength Cond Res*, Vol. 29, pp. 1339–1348, May 2015.

69. García-Manso, J. M., D. Rodríguez-Matoso, S. Sarmiento, Y. de Saa, D. Vaamonde, D. Rodríguez-Ruiz, and M. E. Da Silva-Grigoletto, "Effect of high-load and high-volume resistance exercise on the tensiomyographic twitch response of biceps brachii," *J Electromyogr Kinesiol*, Vol. 22, pp. 612–619, Aug. 2012.

70. Wiewelhove, T., C. Schneider, A. Döweling, F. Hanakam, C. Rasche, T. Meyer, M. Kellmann, M. Pfeiffer, and A. Ferrauti, “Effects of different recovery strategies following a half-marathon on fatigue markers in recreational runners,” *PLoS One*, Vol. 13, Nov. 2018.

71. Valenĉiĉ, V., and N. Knez, “Measuring of Skeletal Muscles’ Dynamic Properties,” *Artificial Organs*, Vol. 21, no. 3, pp. 240–242, 1997.

72. Tous-Fajardo, J., G. Moras, S. Rodríguez-Jiménez, R. Usach, D. M. Doutres, and N. A. Maffiuletti, “Inter-rater reliability of muscle contractile property measurements using non-invasive tensiomyography,” *J Electromyogr Kinesiol*, Vol. 20, pp. 761–766, Aug. 2010.

73. Perotto, A. O., *Anatomical Guide for the Electromyographer: The Limbs and Trunk*, Vol. 86, 2007.

74. Gasparini, M., M. Sabovic, I. D. Gregoric, B. Simunic, and R. Pisot, “Increased fatigability of the gastrocnemius medialis muscle in individuals with intermittent claudication,” *Eur J Vasc Endovasc Surg*, Vol. 44, pp. 170–176, Aug. 2012.

75. Raeder, C., T. Wiewelhove, R. Simola, M. Kellmann, T. Meyer, M. Pfeiffer, and A. Ferrauti, “Assessment of Fatigue and Recovery in Male and Female Athletes After 6 Days of Intensified Strength Training,” *J Strength Cond Res*, Vol. 30, pp. 3412–3427, Dec. 2016.

76. Kokkonen, J., A. G. Nelson, and A. Cornwell, “Acute muscle stretching inhibits maximal strength performance,” *Res Q Exerc Sport*, Vol. 69, pp. 411–415, Dec. 1998.

77. Simuniĉ, B., H. Degens, J. Rittweger, M. Narici, I. B. Mekjavić, and R. Pišot, “Noninvasive estimation of myosin heavy chain composition in human skeletal muscle,” *Med Sci Sports Exerc*, Vol. 43, pp. 1619–1625, Sept. 2011.

78. Križaj, D., B. Šimunič, and T. Žagar, “Short-term repeatability of parameters extracted from radial displacement of muscle belly,” *Journal of Electromyography and Kinesiology*, Vol. 18, pp. 645–651, Aug. 2008.

79. Rey, E., C. Lago-Peñas, J. Lago-Ballesteros, and L. Casáis, “The effect of recovery strategies on contractile properties using tensiomyography and perceived muscle soreness in professional soccer players,” *J Strength Cond Res*, Vol. 26, pp. 3081–3088, Nov. 2012.

80. Macgregor, L. J., A. M. Hunter, C. Orizio, M. M. Fairweather, and M. Ditroilo, “Assessment of Skeletal Muscle Contractile Properties by Radial Displacement: The Case for Tensiomyography,” *Sports Med*, Vol. 48, no. 7, pp. 1607–1620, 2018.

81. McManus, L. M., and R. N. Mitchell, *Pathobiology of Human Disease*, 2014.

82. Waldman, S. D., and R. S. Campbell, *Imaging of Pain*, Elsevier, 2011.

83. Thirion, J. P., “Image matching as a diffusion process: an analogy with Maxwell’s demons,” *Med Image Anal*, Vol. 2, pp. 243–260, Sept. 1998.

84. Heemskerk, A. M., T. K. Sinha, K. J. Wilson, Z. Ding, and B. M. Damon, “Repeatability of DTI-based skeletal muscle fiber tracking: Repeatability of DTI-based fiber tracking,” *NMR Biomed.*, Vol. 23, pp. 294–303, Apr. 2010.

85. Tench, C., “White matter mapping using diffusion tensor MRI - Magnetic Resonance in Medicine -,” 2002.

86. Słupik, A., M. Dwornik, D. BiaÅoszewski, and E. Zych, "Effect of Kinesio Taping on bioelectrical activity of vastus medialis muscle. Preliminary report," *Ortop Traumatol Rehabil*, Vol. 9, pp. 644–651, Dec. 2007.

87. Pamuk, U., and C. A. Yucesoy, "MRI analyses show that kinesio taping affects much more than just the targeted superficial tissues and causes heterogeneous deformations within the whole limb," *J Biomech*, Vol. 48, pp. 4262–4270, Dec. 2015.

88. Hsu, Y.-H., W.-Y. Chen, H.-C. Lin, W. T. J. Wang, and Y.-F. Shih, "The effects of taping on scapular kinematics and muscle performance in baseball players with shoulder impingement syndrome," *J Electromyogr Kinesiol*, Vol. 19, pp. 1092–1099, Dec. 2009.

89. Grześkowiak, M., Z. Krawiecki, W. Łabędź, J. Kaczmarczyk, J. Lewandowski, and D. Łochyński, "Short-Term Effects of Kinesio Taping on Electromyographic Characteristics of Paraspinal Muscles, Pain, and Disability in Patients With Lumbar Disk Herniation," *Journal of Sport Rehabilitation*, Vol. 28, pp. 402–412, July 2019.

90. Lins, C., F. Locks, A. Amorim, L. Brito Macedo, and J. Brasileiro, "Kinesio taping does not alter neuromuscular performance of femoral quadriceps or lower limb function in healthy subjects: randomized, blind, controlled, clinical trial," *Man Ther*, Vol. 18, pp. 41–45, Feb. 2013.

91. Sun, W., Y. Qi, Y. Sun, T. Zhao, X. Su, and Y. Liu, "Optimization of Surface Electromyography-Based Neurofeedback Rehabilitation Intervention System," *Journal of Healthcare Engineering*, Vol. 2021, p. e5546716, Mar. 2021. Publisher: Hindawi.

92. Ryan, D. S., S. Domínguez, S. A. Ross, N. Nigam, and J. M. Wakeling, "The Energy of Muscle Contraction. II. Transverse Compression and Work," *Front. Physiol.*, Vol. 11, 2020. Publisher: Frontiers.

93. Tegner, Y., and J. Lysholm, "Rating systems in the evaluation of knee ligament injuries," *Clin. Orthop. Relat. Res.*, pp. 43–49, Sept. 1985.

94. Lohr, C., K.-M. Braumann, R. Reer, J. Schroeder, and T. Schmidt, "Reliability of tensiomyography and myotonometry in detecting mechanical and contractile characteristics of the lumbar erector spinae in healthy volunteers," *Eur. J. Appl. Physiol.*, Vol. 118, pp. 1349–1359, July 2018.

95. Martín-Rodríguez, S., I. Loturco, A. M. Hunter, D. Rodríguez-Ruiz, and D. Munguia-Izquierdo, "Reliability and Measurement Error of Tensiomyography to Assess Mechanical Muscle Function: A Systematic Review," *J Strength Cond Res*, Vol. 31, pp. 3524–3536, Dec. 2017.

96. Cohen, J., "A power primer," *Psychological Bulletin*, Vol. 112, no. 1, pp. 155–159, 1992. Place: US Publisher: American Psychological Association.

97. Schleip, R., "Fascial plasticity â a new neurobiological explanation: Part 1," *Journal of Bodywork and Movement Therapies*, Vol. 7, pp. 11–19, Jan. 2003. Publisher: Elsevier.

98. De Domenico, G., and D. I. McCloskey, "Accuracy of voluntary movements at the thumb and elbow joints," *Exp Brain Res*, Vol. 65, pp. 471–478, Jan. 1987.

99. Woittiez, R., P. Huijing, and R. Rozendal, "Twitch characteristics in relation to muscle architecture and actual muscle length," *Pflugers Arch.*, Vol. 401, pp. 374–379, Aug. 1984.

100. Azizi, E., A. Deslauriers, N. Holt, and C. Eaton, “Resistance to radial expansion limits muscle strain and work,” *Biomech Model Mechanobiol*, Vol. 16, pp. 1633–1643, Oct. 2017.

101. Alexander, C., S. Stynes, A. Thomas, J. Lewis, and P. Harrison, “Does tape facilitate or inhibit the lower fibres of trapezius?,” *Man Ther*, Vol. 8, pp. 37–41, Feb. 2003.

102. Reynard, F., P. Vuistiner, B. Léger, and M. Konzelmann, “Immediate and short-term effects of kinesiotaping on muscular activity, mobility, strength and pain after rotator cuff surgery: a crossover clinical trial,” *BMC musculoskeletal disorders*, Vol. 19, p. 305, Aug. 2018.

103. Turkoglu, A. N., P. Huijing, and C. Yucesoy, “Mechanical principles of effects of botulinum toxin on muscle length-force characteristics: an assessment by finite element modeling,” *J Biomech*, Vol. 47, pp. 1565–1571, May 2014.

104. Ateş, F., R. Andrade, S. Freitas, F. Hug, L. Lacourpaille, R. Gross, C. Yucesoy, and A. Nordez, “Passive stiffness of monoarticular lower leg muscles is influenced by knee joint angle,” *Eur J Appl Physiol*, Vol. 118, pp. 585–593, Mar. 2018.

105. Ateş, F., Y. Temelli, and C. A. Yucesoy, “Intraoperative experiments show relevance of inter-antagonistic mechanical interaction for spastic muscle’s contribution to joint movement disorder,” *Clin Biomech (Bristol, Avon)*, Vol. 29, pp. 943–949, Sept. 2014.

106. Ateş, F., O. Aytürk, Y. Temelli, and C. Yucesoy, “Human spastic Gracilis muscle isometric forces measured intraoperatively as a function of knee angle show no abnormal muscular mechanics,” *Clin Biomech (Bristol, Avon)*, Vol. 28, pp. 48–54, Jan. 2013.

107. Kaya Keles, C. S., F. Bilgili, E. Akalan, and C. Yucesoy, “Intraoperative testing of passive and active state mechanics of spastic semitendinosus in conditions involving intermuscular mechanical interactions and gait relevant joint positions,” *J Biomech*, Vol. 103, p. 109755, Apr. 2020.

108. Kaya, C. S., F. Bilgili, N. E. Akalan, Y. Temelli, F. Ateş, and C. A. Yucesoy, “Intraoperative experiments combined with gait analyses indicate that active state rather than passive dominates the spastic gracilis muscle’s joint movement limiting effect in cerebral palsy,” *Clin Biomech (Bristol, Avon)*, Vol. 68, pp. 151–157, Aug. 2019.

109. Lin, Y.-F., J.-J. Lin, M.-H. Jan, T.-C. Wei, H.-Y. Shih, and C.-K. Cheng, “Role of the vastus medialis obliquus in repositioning the patella: a dynamic computed tomography study,” *Am J Sports Med*, Vol. 36, pp. 741–746, Apr. 2008.

110. Csapo, R., and L. M. Alegre, “Effects of Kinesio taping on skeletal muscle strength-A meta-analysis of current evidence,” *J Sci Med Sport*, Vol. 18, pp. 450–456, July 2015.

111. Thelen, M., J. Dauber, and P. Stoneman, “The Clinical Efficacy of Kinesio Tape for Shoulder Pain: A Randomized, Double-Blinded, Clinical Trial,” *J Orthop Sports Phys Ther*, Vol. 38, pp. 389–395, July 2008. Publisher: Journal of Orthopaedic & Sports Physical Therapy.

112. Williams, S., C. Whatman, P. A. Hume, and K. Sheerin, “Kinesio taping in treatment and prevention of sports injuries: a meta-analysis of the evidence for its effectiveness,” *Sports Med*, Vol. 42, pp. 153–164, Feb. 2012.

113. Tu, S., R. Woledge, and D. Morrisey, “Does kinesio tape alter thoracolumbar fascia movement during lumbar flexion? an observational laboratory study,” *Journal of Bodywork and Movement Therapies*, Vol. 20, no. 4, pp. 895–905, 2016.

114. Adstrum, S., G. Hedley, R. Schleip, C. Stecco, and C. A. Yucesoy, "Defining the fascial system," *Journal of Bodywork and Movement Therapies*, Vol. 21, pp. 173–177, Jan. 2017.

115. Hedley, G., "Notes on visceral adhesions as fascial pathology," *J Bodyw Mov Ther*, Vol. 14, pp. 255–261, July 2010.

116. Huijing, P., A. Yaman, C. Öztürk, and C. Yucesoy, "Effects of knee joint angle on global and local strains within human triceps surae muscle: MRI analysis indicating in vivo myofascial force transmission between synergistic muscles," *Surg Radiol Anat*, Vol. 33, pp. 869–879, Dec. 2011.

117. Yaman, A., C. Ozturk, P. A. Huijing, and C. A. Yucesoy, "Magnetic resonance imaging assessment of mechanical interactions between human lower leg muscles in vivo," *J Biomech Eng*, Vol. 135, p. 91003, Sept. 2013.

118. Kuo, Y. L., and Y. C. Huang, "Effects of the application direction of kinesio taping on isometric muscle strength of the wrist and fingers of healthy adults - A pilot study," *Journal of Physical Therapy Science*, Vol. 25, no. 3, pp. 287–291, 2013. Publisher: Society of Physical Therapy Science (Rigaku Ryoho Kagakugakkai).

119. Purslow, P. P., "Muscle fascia and force transmission," *J Bodyw Mov Ther*, Vol. 14, pp. 411–417, Oct. 2010.

120. Berthier, C., and S. Blaineau, "Supramolecular organization of the subsarcolemmal cytoskeleton of adult skeletal muscle fibers. A review," *Biol Cell*, Vol. 89, pp. 413–434, Oct. 1997.

121. Huijing, P. A., "Muscle as a collagen fiber reinforced composite: a review of force transmission in muscle and whole limb," *J Biomech*, Vol. 32, pp. 329–345, Apr. 1999.

122. Pamuk, U., A. Çankaya, and C. Yucesoy, "Principles of the Mechanism for Epimuscular Myofascial Loads Leading to Non-uniform Strain Distributions Along Muscle Fiber Direction: Finite Element Modeling," *Front Physiol*, Vol. 11, p. 789, 2020.

123. Klein, S., M. Staring, K. Murphy, M. A. Viergever, and J. P. W. Pluim, "elastix: a toolbox for intensity-based medical image registration," *IEEE Trans Med Imaging*, Vol. 29, pp. 196–205, Jan. 2010.

124. Burkholder, T. J., "Mechanotransduction in skeletal muscle," *Front Biosci*, Vol. 12, pp. 174–191, Jan. 2007.

125. Yucesoy, C. A., and P. A. Huijing, "Specifically tailored use of the finite element method to study muscular mechanics within the context of fascial integrity: The linked fiber-matrix mesh model," *JMC*, Vol. 10, no. 2, 2012. Publisher: Begel House Inc.

126. Yucesoy, C., B. Koopman, P. Huijing, and H. Grootenboer, "Three-dimensional finite element modeling of skeletal muscle using a two-domain approach: linked fiber-matrix mesh model," *J Biomech*, Vol. 35, pp. 1253–1262, Sept. 2002.

127. Purslow, P. P., "The Structure and Role of Intramuscular Connective Tissue in Muscle Function," *Front Physiol*, Vol. 11, p. 495, May 2020.

128. Purslow, P. P., and J. A. Trotter, "The morphology and mechanical properties of endomysium in series-fibred muscles: variations with muscle length," *J Muscle Res Cell Motil*, Vol. 15, pp. 299–308, June 1994.

129. Huxley, H. E., "The double array of filaments in cross-striated muscle," *J Biophys Biochem Cytol*, Vol. 3, pp. 631–648, Sept. 1957.

130. Azizi, E., and A. R. Deslauriers, "Regional heterogeneity in muscle fiber strain: the role of fiber architecture," *Front. Physiol.*, Vol. 5, 2014. Publisher: Frontiers.

131. Willems, M. E., and P. A. Huijing, "Heterogeneity of mean sarcomere length in different fibres: effects on length range of active force production in rat muscle," *Eur J Appl Physiol Occup Physiol*, Vol. 68, no. 6, pp. 489–496, 1994.

132. Ateş, F., R. Özdeşlik, P. Huijing, and C. Yucesoy, "Muscle lengthening surgery causes differential acute mechanical effects in both targeted and non-targeted synergistic muscles," *J Electromyogr Kinesiol*, Vol. 23, pp. 1199–1205, Oct. 2013.

133. Jaspers, R. T., R. Brunner, G. C. Baan, and P. A. Huijing, "Acute effects of intramuscular aponeurotomy on rat gastrocnemius medialis: force transmission, muscle force and sarcomere length," *Journal of biomechanics*, Vol. 32, Jan. 1999. Publisher: J Biomech.

134. Ateş, F., and C. A. Yucesoy, "Botulinum toxin type-A affects mechanics of non-injected antagonistic rat muscles," *J Mech Behav Biomed Mater*, Vol. 84, pp. 208–216, Aug. 2018.

135. Yilmaz, E., C. S. Kaya Keles, Z. Akdeniz, and C. Yucesoy, "Long-term BTX-A effects on bi-articular muscle: Higher passive force, limited length range of active force production and unchanged intermuscular interactions," *J Biomech*, Vol. 126, p. 110627, Sept. 2021.

136. Kumagai, K., T. Abe, W. F. Brechue, T. Ryushi, S. Takano, and M. Mizuno, "Sprint performance is related to muscle fascicle length in male 100-m sprinters," *Journal of applied physiology (Bethesda, Md. : 1985)*, Vol. 88, Mar. 2000. Publisher: J Appl Physiol (1985).

137. Bland, D., L. Prosser, L. Bellini, K. Alter, and D. Damiano, "Tibialis anterior architecture, strength, and gait in individuals with cerebral palsy," *Muscle Nerve*, Vol. 44, pp. 509–517, Oct. 2011.

138. Yildiz, S., U. Pamuk, G. Baltaci, and C. A. Yucesoy, "Effects of Kinesio Taping on Muscle Contractile Properties: Assessment Using Tensiomyography," *J Sport Rehabil*, Vol. 31, pp. 263–270, Mar. 2022.

139. Chaitow, L., "Fascia's function: classical osteopathic perspectives and current research compared," *J Bodyw Mov Ther*, Vol. 17, p. 355, July 2013.