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Fascia research – A narrative review

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Summary This article reviews fascia research from our laboratory and puts this in the context of recent progress in fascia research which has greatly expanded during the past seven or eight years. Some readers may not be familiar with the terminology used in fascia research articles and are referred to LeMoon (2008) for a glossary of terms used in fascia-related articles.

Introduction

Fascia is the soft tissue component of the connective tissue system that permeates the human body forming a whole body continuous three dimensional matrix of structural support (Fascia Research Congress 2007). It is a viscoelastic matrix which envelops muscles, bones and organs and is a continuous network throughout the body. It plays an important role in transmitting mechanical forces between muscles (Huijing, 2009) and therapies directed to fascia may improve balance and posture (DellaGrotte, 2008). With acute inflammation, fascia tightens and loses its pliability. Long term postural positioning which prevents full excursion of the fascia, and possibly some short term processes may also shorten fascia. When this happens, stretch of the fascia to what was previously a pain free range may cause pain to be felt at distant sensitive areas such as nerves and blood vessels. By releasing its tightness by manual therapy or other techniques, pressure is relieved on these areas and blood circulation becomes normal (Walton, 2008). Fascia also has piezoelectric properties i.e. changing mechanical force into electric energy (Rivard et al., 2011). Some clinical therapies claim to change fascia from viscous gel state to less viscous sol state (Juhan, 1987) particularly the application of heat, active or passive movement and soft tissue manipulation (Chaitow and Delany, 2003). Luigi Stecco (2004) concludes "Fascia is the only tissue that modifies its consistency when under stress (plasticity) and which is capable of regaining its elasticity when subjected to manipulation (malleability). It coordinates components of motor units in the myofascial unit and connects element between body joints by means of retinaculas. The fascia and the muscles act as rigging that guarantees verticality of

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FASCIA SCIENCE AND CLINICAL APPLICATIONS: MATHEMATICAL FASCIAL MODELLING

a layer of connective tissue that wraps muscle and is composed mostly of reticular fibers. The weighted mean angle of orientation is 59.1°. As the sarcomere length of the muscle increases, the mean fiber angle also increases (Purslow and Trotter, 1994).

12. Our analysis deals primarily with manually applied therapies. Different approaches may be necessary for techniques such as Graston Technique (GT) which focus forces using an instrument-assisted, soft tissue mobilization method (Warren et al., 2008).
13. Rotational Oscillations applied to the low back of normal subjects with a BMI less than or equal to 25 improved the mechanical properties of the low back (Chaudhry et al., 2011).

Directions for future research

1. Fascia may have a key role in proprioception due to the presence of mechanoreceptors, which work primarily under the influence of tension. The transmission of tensile forces to receptors can be a fruitful area of investigation (Chaudhry, 2011).
2. Demonstration of the existence of a connective signaling network may profoundly influence our understanding of health and disease (Langevin 2007).
3. Determination of In- vivo Visco elastic Mechanical Properties of Fasciae at multiple locations in the human body may profoundly influence design of manual therapy interventions.
4. Fascia is considered to be a piezoelectric material of second harmonic generation (Rivard et al., 2011) that changes mechanical forces applied to fascia into electric energy. The changes in the mechanical properties of fascia before and after manual therapies due to the piezoelectric effects may be a fruitful area of research.

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edge contoured to fit various shapes of the body. Warren reports three case studies including supraspinatus tendinosis, Achilles tendinosis, and plantar fasciosis. This method resulted in the elimination of pain in the above mentioned cases. He hypothesizes that the increased mechanical loading increases fibroblastic proliferation resulting in improved healing.

Anatomy of fascia

A fascia is a connective tissue that surrounds muscles, groups of muscles, blood vessels, and nerves. It consists of several layers: a superficial fascia, a deep fascia, and a subserous (or visceral) fascia. The superficial fascia is a fibrous layer with a membranous appearance, appearing continuous and well organized macroscopically. From a histological point of view, it is a fibro-elastic tissue in which elastic fibers are abundant and well organized and show an undulating course. Irregular islands of thin sublayers of fat cells may be deposited between layers of collagen fibers. Therefore, while macroscopically the membranous layer appears and can be isolated as a well-defined membrane, microscopically its structure is better described as lamellar, or like a tightly packed honeycomb (Lancerotto et al., 2009).

The deep fascia of the pectoral region is morphologically and functionally different from that of the thigh: the fascia lata is a relatively autonomous structure with respect to the underlying muscular plane, while the pectoralis fascia acts as an additional insertion for the pectoralis major muscle. The histological study demonstrates that the fascia in the trunk region is formed by a single layer of undulated collagen fibers, intermixed with many elastic fibers. In the thigh, the deep fascia is independent from the underlying muscle, separated by the epimysium and a layer of loose connective tissue (Fig. 6). In the thigh, the epimysium is easily recognizable under the deep fascia and presents a mean thickness of 48 mm. An epimysial fascia, or epimysium, is not distinguished between this fascia and the underlying muscle, but many muscular fibers of the pectoralis major muscle are in continuity with the pectoral fascia itself (Stecco et al., 2009).

Purslow and Trotter (1994) reported that the angle of fiber orientation varies in endomysium (a type of fascia) from 2.5° to 87.5°. The endomysium is a layer of connective tissue that wraps muscle and is composed mostly of reticular fibers. The weighted mean angle of orientation is 59.1°. As the sarcomere length of the muscle increases, the mean fiber angle also increases.

The deep fascia is a membrane that extends throughout the whole body and numerous muscular expansions maintain it in a basal tension. As Van der Wal (2009) demonstrates, ligaments crossing joints are not separate entities from the surrounding muscle and fascia, but the ligamentous tension can vary at different joint positions depending on the neighboring muscle activity. During a muscular contraction these fascial expansions can transmit the tension generated by the muscle to neighboring areas, stimulating the proprioceptors in that area (Fig. 7) (Stecco et al., 2007). Thus fascia itself may be an important factor in maintenance of joint stability.

Summary

1. Fascia Lata and Plantar Fascia are very stiff. Very large forces, outside the physiological range are required to produce 1% compression and 1% shear. This is not the case for superficial nasal fascia, a soft tissue (Chaudhry et al., 2008). The palpable sensations of tissue release that are often reported by osteopathic physicians and other manual therapists cannot be due to deformations produced in the firm tissues of plantar fascia and fascia lata. However, palpable tissue release can result from deformation in softer tissues, such as superficial nasal fascia.
2. Fascia Lata (in vitro) and plantar fascia (in vitro) are found to have similar behavior under extension. Greater loads are needed to produce the same strain with a higher rate of extension. The predicted stiffness in extension for plantar fascia, fascia lata and superficial nasal fascia are 404, 477, and 1 MPa respectively. The stiffness for nasal fascia is tiny compared to the other fasciae (Chaudhry et al., 2007a).
3. With quick maneuvers in manual therapy treatment, the visco elasticity effect is decreased. The biceps muscle is 15 times stiffer in the direction parallel to the muscle fibers than in the direction perpendicular to the fibers (Chaudhry et al., 2007b).
4. The bending stress is 450 times greater than the twisting stress for the same angle of twist or bending of the annulus fibrosus. In patients suffering from low back pain with a disk mediated (discogenic) component, with manipulation and mobilization therapies our calculations suggest avoiding flexion to minimize stress on the disk. This is particularly relevant for high velocity manipulation (Chaudhry et al., 2009).
5. There are no significant differences in age, sex, body mass index or activity level between low back pain (LBP) and No- LBP groups. The LBP have approximately 25% greater perimuscular thickness and echogenicity in the lumber region compared with No-LBP (Langevin et al., 2009).
6. It is observed that for greater fiber angle orientation, the fibers are more resistant to reorientation as the fascia is stretched longitudinally (Chaudhry et al., 2011).
7. The apparent longitudinal stiffness of the endomysium is greater than the true translaminar shear modulus of the endomysium with a magnitude of 4×10^6(Purslow, 2010).
8. Fascia is generally considered as a structure which bears tensile and not compressive force. We show both tension and compression forces within fascia. But the sum total of tension and compression (negative tension) is positive tension. Therefore, the fascia is always in tension (Chaudhry, 2011).
9. Elastic modulus of passive muscle in stretch is 10 kPa compared to 20 kPa of rubber, meaning muscle is softer than rubber.
10. The matrix of the fascia, which surrounds the collagen fibers consists of a proteoglycan gel with negligible modulus of elasticity in tension in relation to the collagen fibers which have a modulus of elasticity as high as 1 GPa (Fung, 1981).
11. The angle of fiber orientation varies in endomysium (a type of fascia) from 2.5° to 87.5°. The endomysium is

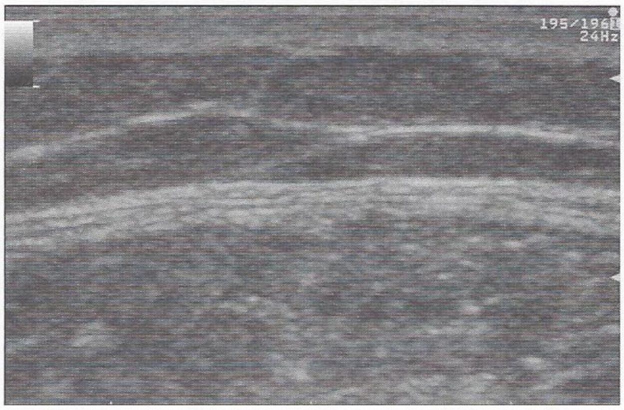

Figure 6 Ultrasonography (10 MHz) of the proximal region of the thigh.

fashion to Langers lines used to plan skin incisions (Crumpler and Chaudhry, 2001).

Manual therapies

We have reported both case studies and larger case series of effects of manual therapies. Findley (2007) reported a case of muscular dystonia of the eyes (benign essential blepharospasm), in which spasms of the eyes were triggered by postural change and deep touch to the lateral chest and posterior calf. After 10 sessions of structural integration (Rolfing®), overall symptoms improved and triggering of spasms were less severe. We also found improvements in range of motion in a larger sample of persons with neck pain (James et al., 2009).

We have reported improvement in balance (Neurocom Equitest Sensory Organization test) in persons with chronic fatigue who had treatment with structural integration (Findley et al., 2007). DellaGrotte (2008) studied twenty five static and dynamic postural parameters on 27 subjects (13 control and 14 experimental receiving two months of core integration intervention). There was significant improvement in the global score for the experimental group compared to the control group.

We have earlier reported on our research on force and deformation with manual therapies with the therapist hands applying all the forces to the patient. However, there are other therapeutic techniques such as Chinese Gua sha, in which the therapist uses an instrument (traditionally made of metal, horn or bone) in order to apply compressive press-stroking force to the patient (Nielsen, 2009). This concentrates local application of forces in a way not possible with hands-only techniques. This mechanical stimulation of soft tissues may result in tissue production of mechano-growth factor which activates muscle cells, with change to muscle as well as fascial tissue (Hill et al., 2003). Warren et al., 2008 reported on an instrument-assisted, soft tissue mobilization method (Graston Technique), which is a patented treatment, using stainless steel instruments designed with a unique, curvilinear treatment

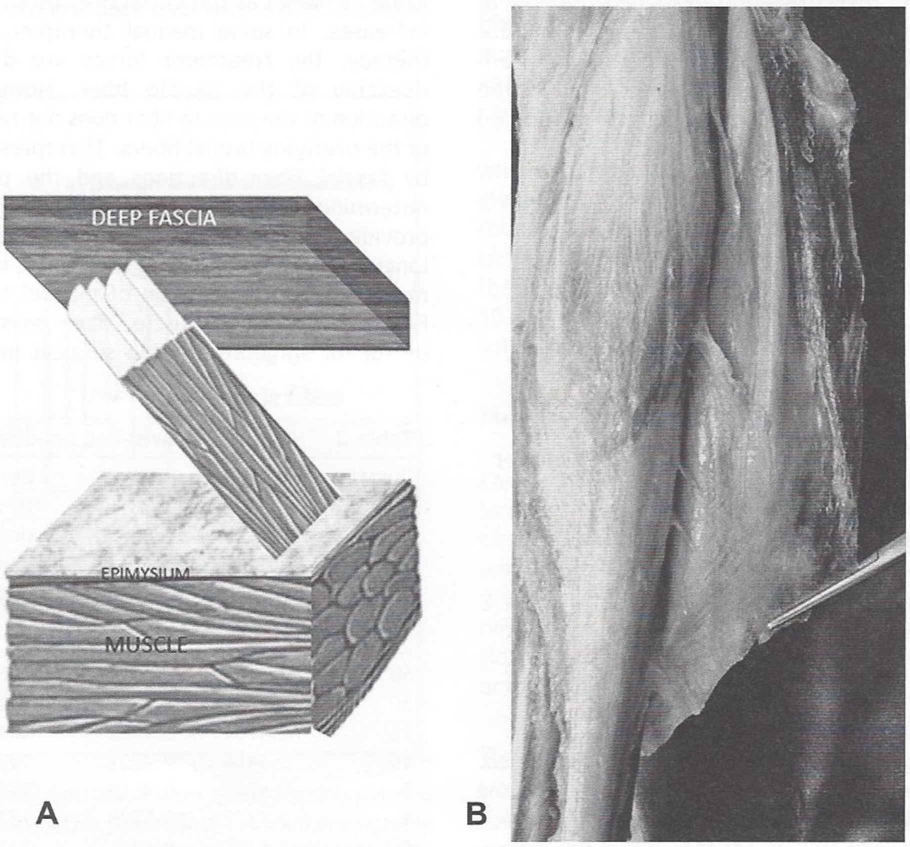

Figure 7 Model of muscle insertion into the deep fascia.

Table 2 Summary of results for all subjects before and after treatment with oscillations.

Subject	Age	Sex	Weight pounds	Height	BMI	Change in HLA	Rotational stiffness	
							Right	Left
1	24	MALE	143	5′9″	21	−30%	8.00%	0.00%
2	24	MALE	154	5′8″	23	−75%	5.00%	11.00%
3	22	FEMALE	119	5′4″	20	−51%	−1.20%	−11.70%
4	77	MALE	167	5′8″	25	−45%	−6.11%	−05.60%
5	39	MALE	150	5′11″	21	−98%	1.20%	0.00%
6	23	MALE	143	5′11″	20	−55%	−1.60%	2.30%
7	23	MALE	160	5′6″	26	14%	2.70%	−1.30%
8	25	MALE	141	5′8″	21	−97%	1.70%	0.40%
9	24	MALE	200	5′6″	32	47%	2.00%	−1.00%
10	24	MALE	204	5″11	28	46%	−2.00%	2.70%

at large displacement, keeping in mind the relevance to biological material. Their findings predict the reorientation of fibers with strain, which agrees with preliminary experimental results from spinal ligaments. No assumption was made about stress transfer to the fibers. Aspden, however, confined his analysis to the fibers in tension, not in compression.

Collagen fibers in one layer are typically oriented in the same direction. In the adjacent layer, fibers go the same direction within the layer, but in a different direction than the neighboring fibers. Surprisingly, a similar fiber orientation in adjacent fascia layers (78° difference between layers) has been observed in diverse locations and different species (Benetazzo et al., 2011; Purslow, 2010). Therefore, we (Chaudhry et al., 2011) recently examined the role of fiber orientation in fascia when analyzed as a composite material. We observed that for greater fiber angle orientation, the fibers are more resistant to reorientation as the fascia is stretched longitudinally. We find that reinforced

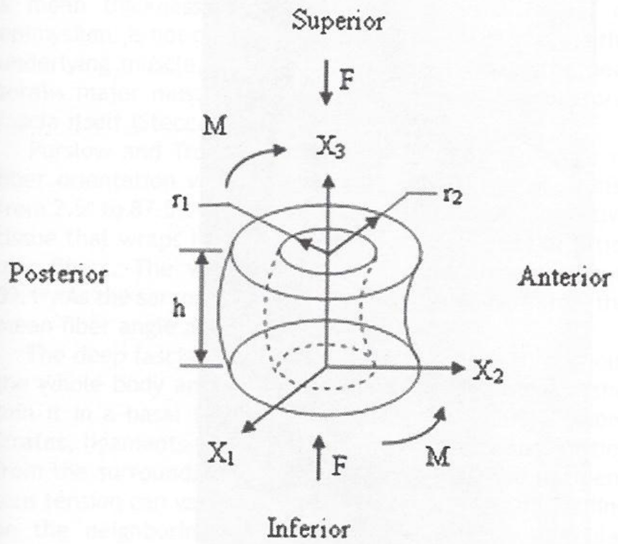

Figure 5 AF disk under compression and bending combined. F is the compressive force. M is the bending moment, h is the height of the disk. r_1, r_2 are the internal and the external radii of the annulus fibrosus. X_1, X_2, X_3 are the axes in the rectangular Cartesian coordinate system.

fascia when looked at as a reinforced composite material can bear compressive as well as tensile forces. The tissue as a whole is under net tension when stretched because the sum total of tension and compression (negative tension) is always positive. However, there are some elements within the tissue which are under compression. For example, an inflated balloon is under uniform tension. When one squeezes one part of the balloon, one creates local areas of compression and other areas of increased tension with the net sum remaining in tension. It is also observed that for a given value of fiber orientation in degrees relative to the horizontal axis in the middle of the fascia, there is a critical value of the stretch below which the summed tension in the fibers is positive and above which it is negative. This critical value increases as the initial orientation angle of the fibers increases. In some manual therapies, like "cross fiber" therapy, the treatment forces are directed across the direction of the muscle fiber. However, knowing the direction of the muscle fiber does not tell you the direction of the overlying fascial fibers. Therapies are not yet defined by fascial fiber directions and the practitioner usually determines force direction by clinical judgment only. We provide a means to model manual therapy interventions in longitudinal and transverse directions, which may allow for more precise specification of manual therapy techniques. Fascial, as well as muscle, fiber directions may also be useful for surgeons to plan surgical incisions in a similar

Table 3 Viscoelastic twist and bending moments.

Duration T_0 (s)	Twist moment Mz (N-cm, max) for 10 deg twist per unit height combined with compression		Bending moment M (N-cm, max) for 10 deg bending combined with compression	
	Linear	Parabolic	Linear	Parabolic
60	0.3462	0.3274	156.2906	147.8249
30	0.3821	0.3633	172.5125	164.0004
15	0.4199	0.4022	189.5420	181.5518
10	0.4414	0.4251	199.2622	191.8940
5	0.4747	0.4618	214.3176	208.4763
1	0.5272	0.5225	237.9858	235.8933
0.1	0.6373	0.6371	287.6914	287.6280

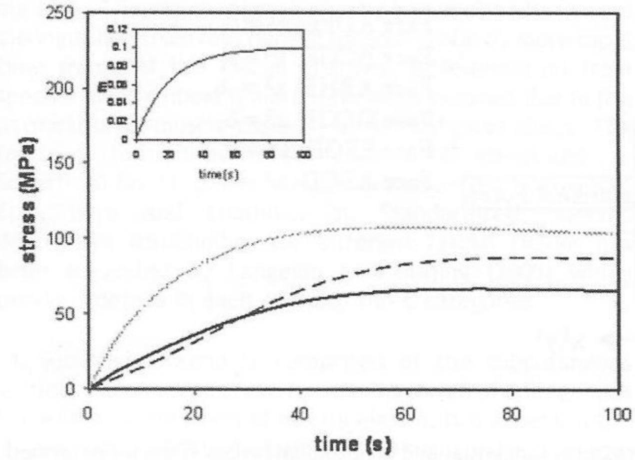

Figure 3 σ_1 (MPa) versus time (s) calculated from the deformation function Eq. (5) for three different cases. Solid curve: fascia lata (in vitro); dashed curve: plantar fascia (in vitro); grey curve: superficial nasal fascia (magnified by 1000 times). The strain-time curve is presented in the inset.

bending (Fig. 5). With a constant 6% compression of the transversely isotropic annulus fibrosus of the lumbar disk, we compared 10° twist with 10° bending. Stress—Strain relation showed that the bending stress is 450 times greater than the twisting stress for the same angle of twist or bending of the annulus fibrosus. The twisting and bending moments for a given displacement increase twofold in quick maneuvers lasting 0.1 s (Table 3). We conclude that in patients suffering from low back pain with a disk mediated

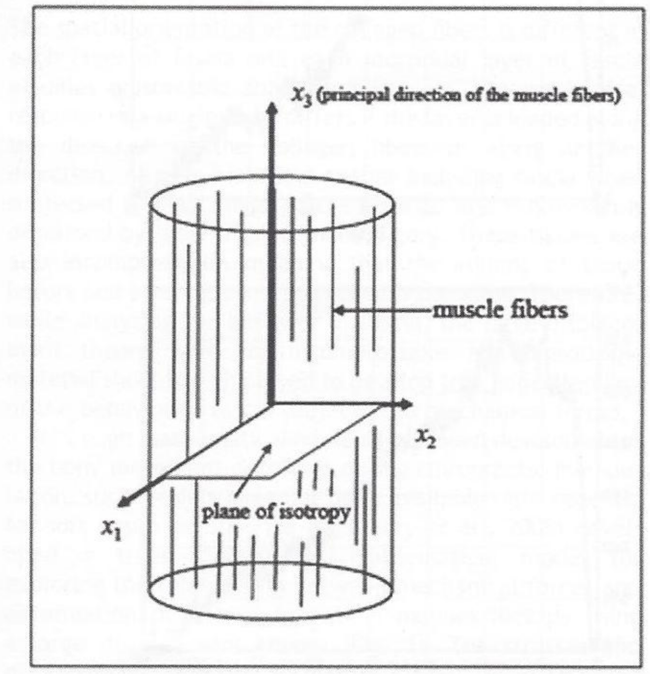

Figure 4 Transversely isotropic biceps muscle. x_1, x_2 plane is a plane of isotropy, i.e. in this plane elastic moduli are same in all directions. Elastic property along x_3 axis is different from the elastic properties in x_1, x_2 plane.

Table 1

Time (s)	Viscoelastic stress produced (kPa)
60	12.0
30	13.2
5	16.5
2	17.0
0.25	18.2

(discogenic) component, manipulation and mobilization therapies should avoid flexion to minimize stress on the disk. This is particularly relevant for high velocity manipulation.

In a larger context, Solomonov (2004) studied the role of ligaments in work-related musculoskeletal disorders. Creep, tension-relaxation, hysteresis, and sensitivity to strain rate resulting from exposure to occupational activities were shown to cause motor disorders with implications for functional disability.

Purslow (2010) reported that the architectural arrangement of muscle fibers and structures is a key determinant of muscle tissue properties. He found that the apparent longitudinal stiffness of the endomysium is 4×10^6 times greater than the true translaminar shear modulus of the endomysium. The entire assembly of multiple layers has different characteristics than individual layers. When the many layers of endomysium are subjected to shear forces, these forces on adjoining layers combine to result in longitudinal force at one end of the entire assembly. Physically, the endomysium connects two adjacent muscle fibers and facilitates the isometric contractile action of the muscles, and still allows movement between muscle fibers as the muscles contract and relax. The detailed explanation can be found in Purslow (2010).

Purslow (1989) also found that the matrix of the fascia, which surrounds the collagen fibers, consists of a proteoglycan gel with negligible modulus of elasticity in tension in relation to the collagen fibers (collagen modulus of elasticity as high as 1 GPa (Fung, 1981)). Fung (1981) calculated the elastic modulus of stretched passive muscle to be 10 kPa compared to 20 kPa of rubber, meaning muscle is softer than rubber.

Measurement of fascial thickness

Langevin et al., (2009) studied fascial thickness in the lumbar region in a group of 107 human subjects with chronic low back pain (LBP) and compared it with those without low back pain using ultrasound images. The LBP group have approximately 25% greater perimuscular thickness and echogenicity in the lumber region compared with No-LBP, when controlling for age, sex, body mass index and activity levels.

Reinforcement of fascia by collagen fibers

Earlier, Aspden (1986) developed a mathematical model to study the relation between structure and mechanical behavior of fiber-reinforced composite isotropic materials

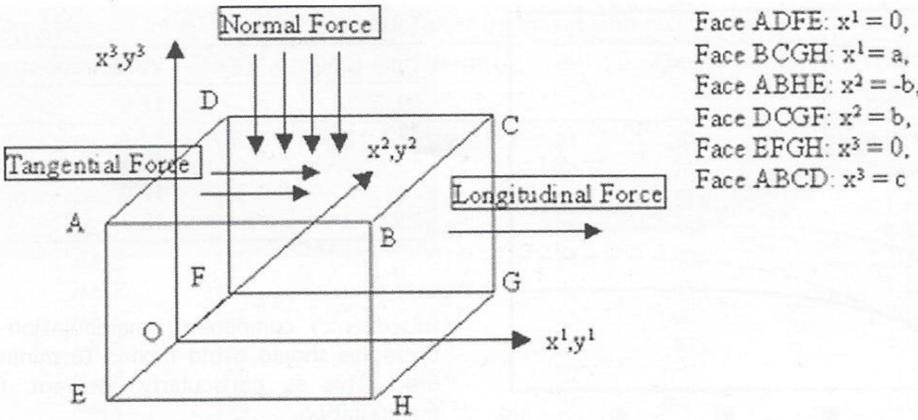

Figure 1 Three dimensional fascial element subjected to normal pressure, tangential and longitudinal forces in the un-deformed state. The axes (x^1, x^2, x^3) in the un-deformed state coincide with the axes (y^1, y^2, y^3) in the deformed state.

We (Chaudhry et al., 2011) evaluated the effect of rotational oscillations on low back function in 10 normal subjects, by determining the change in Hysteresis Loop Area (HLA) (Warner et al., 1997). A smaller HLA is considered to indicate better low back function. These oscillations to the low back were provided for a duration of 5 min at a frequency of 20 cycles per minute. The hysteresis loop was smaller after treatment for those subjects whose BMI was less than or equal to 25 (Table 2).

Twisting (spinal rotation) and bending (flexion) are commonly reported as triggers for low back pain. We (Chaudhry et al., 2009), then, studied whether the twisting stress on the annulus fibrosus of the lumbar disk is greater or less than the bending stress for the same angle of twist or

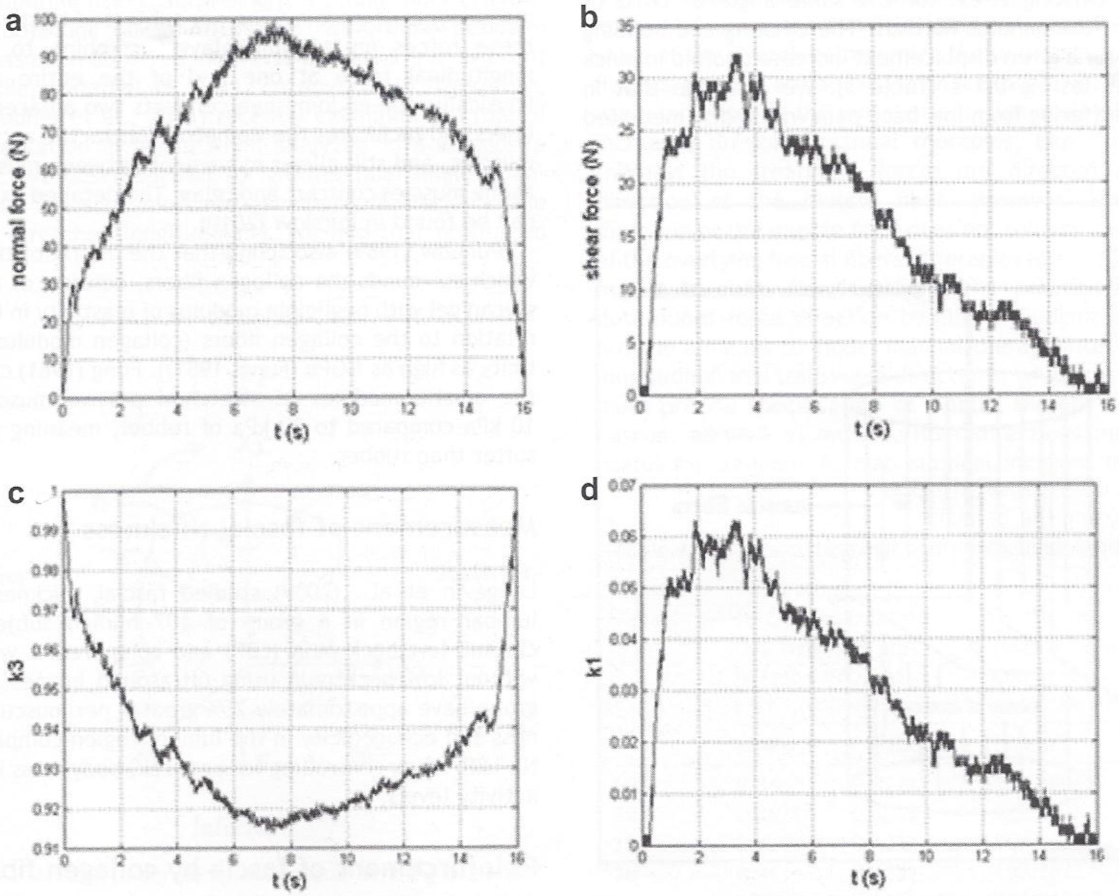

Figure 2 Measured forces during a myofascial release technique on the fascia lata or on the plantar fascia. t(s) denotes time in seconds. a: Fascia lata, applied normal force (in Newton). b: Fascia lata, applied shear force (in Newton). c: Plantar fascia, applied normal force (in Newton). d: Plantar fascia, applied shear force (in Newton).

our body." Fascia changes in response to applied forces are distinguished from reactions of osseous tissue by more rapid time frame of the fascial changes. Differentiation from specific muscle fibers is more difficult to pinpoint due to the permeation of muscle tissue by different fascial layers. The fascia is formed by three fundamental structures: 1. Superficial fascia, 2. Deep fascia, 3. muscle related layers : Epi-, peri- and Endo-mysium. Standardized, specific descriptive terminology for different fascial tissues has been suggested by Langevin and Huijing (2009) which provides details in each of these three categories.

1. Superficial fascia is comprised of the subcutaneous loose connective tissue containing a web of collagen, as well as some fibers of mostly elastin. It is absent in the soles of the feet, the palms of the hand and in the face. Within its meshes, this contains fat.
2. Deep fascia is formed by a connective membrane that sheaths all muscles. It is devoid of fat and forms sheaths for the nerves and vessels, envelops various organs and glands.
3. Epimysium comprises the fascia that encloses each single muscle and is continuous with perimysium and endomysium. It is directly involved in the play of tension between the muscle spindles and the Golgi tendon organs (Stecco, 2004).

In this review fascia is discussed under the following main categories: Biomechanics of Fascia, Measurement of Fascial Changes, Reinforcement of Fascia by Collagen Fibers, Manual Therapies, Anatomy of Fascia.

Biomechanics of fascia

The spatial orientation of the collagen fibers is different in each layer of fascia and each individual layer of fascia assumes anisotropic characteristics, i.e. the mechanical response of a single layer differs if the layer is loaded along the direction of the collagen fibers or along another direction. All soft biological tissues including fascia when subjected to mechanical forces respond in a way which is described by large displacement theory. These tissues are also incompressible, meaning that the volume of tissue before and after deformation remains the same. Therefore, while analyzing the behavior of fascia, the large displacement theory valid for incompressible and anisotropic material should be employed to develop true understanding of the behavior of fascia subjected to mechanical forces.

Although mathematical models have been developed for the bony movement occurring during chiropractic manipulation, such models have not been available until recently for soft tissue motion. We (Chaudhry et al., 2008) developed a three dimensional mathematical model for exploring the relationship between mechanical forces and deformation of human fasciae in manual therapy using a large displacement theory (Fig. 1). The stresses and displacement produced in plantar fascia, fascia lata and superficial nasal fascia by subjecting a volunteer to mechanical forces were then determined by using the elastic constants in vitro. The mechanical forces were measured and the displacement was then theoretically predicted by using the mathematical model (Fig. 2). The importance of developing this model was recognized by the George Northup DO Medical Writing Award which designated this paper as the best article published in *The Journal of the American Osteopathic Association (JAOA)* in 2008.

We found that Fascia Lata and Plantar Fascia are very stiff. Very large forces, outside the physiological range are required to produce even 1% compression and 1% shear. Such is not the case for superficial nasal fascia, which is composed of much softer tissue. We concluded that the palpable sensations of tissue release that are often reported by osteopathic physicians and other manual therapists cannot be due to deformations produced in the firm tissues of plantar fascia and fascia lata. However, palpable tissue release could result from deformation in softer tissues, such as superficial nasal fascia.

We (Chaudhry et al., 2007a) employed the basic field equations for viscoelastic soft tissues to explore the relationship between time-varying mechanical stresses and dynamic deformations of the plantar fascia and fascia lata as well as the softer nasal fascia in manual therapy. The predicted stress range for plastic deformation of plantar fascia, based on the viscoelastic model, was found to be close to experimental findings. In addition, Fascia Lata (in vitro) and plantar fascia (in vitro) are found to have almost similar behavior under extension. With greater extension in a shorter period of time, greater loads are needed to produce the same strain. The predicted stiffness in extension for plantar fascia, fascia lata and superficial nasal fascia are 404, 477, and 1 MPa respectively (Chaudhry et al., 2007a). We conclude that maximum extension can be achieved with stretch of 60 s and further increasing the duration of the stretch will not increase deformation (Fig. 3). This is remarkably close to clinical research findings that 30 s stretch in physical therapy achieves as much as longer stretches (Bandy and Irion, 1994). Longer stretching such as casting for contractures in cerebral palsy, which can last overnight or many days, probably invokes other remodeling mechanisms of both fascia and muscle, rather than just stretching of fascial tissue.

While manual therapies have long focused on stretching in a single direction, recently rotation or twisting has been reported to augment these linear manual therapy techniques (Ward, 2003) and we began to explore this in our modeling. We (Chaudhry et al., 2007b) therefore developed a three dimensional mathematical model to establish the relationship between the applied loads and the resulting deformations produced in twist, compression, shear, and extension of the biceps muscle. We found that the biceps muscle is 15 times stiffer in the direction parallel to the muscle fibers than in the direction perpendicular to the fibers (Fig. 4). We also found that with quick maneuvers such as in high velocity therapy treatment (HVLA), within the ranges of applied forces, the viscoelasticity effect is decreased. An extension of 10% in quick maneuvers lasting 0.25 s reduces viscoelasticity by 50% compared to slow maneuvers lasting 60 s (Table 1). Also extension at a slower rate leads to lower stresses compared to extension at a more rapid rate. Therefore the length of time of the maneuver selected depends on the goal of the manipulation.

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