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REVIEW

Morphometric and dynamic measurements of muscular fascia in healthy individuals using ultrasound imaging: a summary of the discrepancies and gaps in the current literature

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Abstract

Purpose The objectives of this work was to conduct a comprehensive state-of-the art review of the current literature to identify any gaps or discrepancies and summarize the main challenges for obtaining a homogeneous evaluation of muscular fascia in healthy individuals.

Methods An electronic document search using key words and MeSH terms was performed with various databases. Two independent investigators were tasked with the screening of articles and data extraction. A critical appraisal of what is known was then conducted.

Results The literature search identified 65 articles related to healthy facia in the various databases consulted and 20 articles were kept for the review. The thickest portion of the fascia lata (the iliotibial tract) and the plantar fascia are the most often studied muscular fasciae whereas there is paucity of studies on fascia related to other muscles in the body.

Conclusion US imaging is suitable to complement physical examination and for evaluating treatment outcomes. However, the small number of studies and the heterogeneity of the methods did not allow us to establish normal reference values for muscular fascia thickness and to provide strong recommendations about measurement protocols.

Keywords Fascia · Ultrasound imaging · Thickness · Strain · Motion

Introduction

Although fascia is now recognized as an important tissue, its definition and classification are still under debate and vary according to authors and geographical context. Holistic definitions of fascia can be found in the current literature such as the one provided by Kumka and Bonar [27]: "Fascia is an uninterrupted viscoelastic tissue which forms a functional 3-dimensional collagen matrix. It surrounds and penetrates all structures of the body extending from head to toe, thus making it difficult to isolate and develop its nomenclature. It is virtually inseparable from all structures in the body and acts to create continuity amongst tissues to enhance function and support." Another noteworthy definition was derived from a general consensus after the 4th Fascia Congress [1]: "The fascial system consists of the three-dimensional continuum of soft, collagen-containing, loose and dense fibrous connective tissues that permeate the body. The fascial system interpenetrates and surrounds all organs, muscles, bones and nerve fibers, endowing the body with a functional structure, and providing an environment that enables all body systems to operate in an integrated manner." More anatomical definitions also exist such as those proposed in Terminologia Anatomica and Gray's Anatomy [16, 53]. According to Terminologia Anatomica, "fascia consists of sheaths, sheets or other dissectible connective tissue aggregations." The fifth edition of Nomina Anatomica (1983) [38] introduced the terms *fascia superficialis* and *fascia profundal*. However, the generic use of these two terms was not recommended in subsequent editions of Terminologia Anatomica, and in the interest of international understanding, the recommended terms are now *tela subcutanea* (subcutaneous tissue), *fascia musculorum* and *fascia visceralis*. This review

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uses this terminology and focuses on muscular fascia (*fascia musculorum)*, which is considered well-organized, dense, fibrous layers of tissue that interact with muscle. Muscular fascia surrounds and separates muscles, forms sheaths for nerves and vessels, strengthens ligaments around joints, binds structures into a firm compact mass, and transmits muscular force over a distance [1, 2, 28, 56]. Deep fascia is composed of a multi-layered structure formed by two or three layers of densely packed collagen fibers with a layer of loose connective tissue between these fibrous layers [50, 51]. Depending on its thickness and relationship with the underlying muscles, deep fascia can be categorized in two main sub-types: aponeurotic fascia and epimysial fascia [40, 50]. The aponeurotic fascia refers to a well-defined fibrous sheath that envelops and connects a group of muscles and that can be separated from underlying muscles [50]. The fascia lata (deep fascia of the thigh) and the thoracolumbar fascia (anterior and posterior layers) are examples of aponeurotic fascia. The epimysial fascia is thin and composed of well-organized layers of collagen fibers and refers to the epimysium of muscles of the limbs and deep muscles of the trunk [50]. Both the aponeurotic and epimysial fasciae play important roles in movement biomechanics. While the first transmit muscle forces over a distance from one body segment to another [60], the other is more concise, transmitting forces between adjacent synergistic muscular fiber bundles [3].

Recent evidence shows that the fascia plays a key role in myofascial pain and many studies have focused on the possible role of hyaluronan (HA) [8, 33]. Changes to the HA-rich matrix can have dramatic effects on the sliding movement of the fascia [10] showing evident structural alterations [29], these effects can contribute to pain, inflammation and loss of function. Moreover, joint mobility is strongly influenced by the gliding interactions between fascia and the underlying supporting muscle attachments and fascial alteration could potentially lead to poor muscular biomechanics, altered structural alignment and decreased strength and motor coordination [13, 37, 47]. Unfortunately, the morphology and mobility of the fascial system is not typically analyzed by radiologists or surgeons and to date, there are only a few articles on the imaging of fascial disorders and tissue mechanical properties [5, 14, 15, 48, 54]. Current assessment of fascial alteration is primary done by palpation, a moderately reliable skill [36] that provides only subjective qualitative information. Some imaging techniques have been used to evaluate fasciae: computed tomography (CT), magnetic resonance imaging (MRI) and ultrasound (US) imaging.

Computer tomography is a diagnostic imaging method that combines the technology of X-rays with that of a computer. The X-ray beam and detector system is housed in a circular scanner and moves through an arc around the patient and the computer mathematically reconstructs images based on the geometric plots where the measurements were taken [34]. In some cases, it has been used to reveal anatomic details of fascial spaces and planes of the buccomasseteric region [6] or to analyze the fat distribution superficial and deep in the Scarpa's fascial layer in the abdomen [22]. Due to high radiation exposure and the poor quality of deep fascia CT scans, optimization of new techniques has become a priority in routine clinical practice.

Magnetic resonance imaging (MRI) scans do not use X-rays. This imaging techniques is based on the principle that certain atomic nuclei can absorb and emit radio frequency energy when placed in an external magnetic field. MRI scans are primarily used in diagnostic medicine and biomedical research. The aponeurotic fascia appears on MRI scans as lines of low signal intensity that are well-defined within the subcutaneous tissue. Thickening and signal changes in the fascia as well as oedema of adjacent soft tissues can be assessed using MRI imaging. The fascia is more easily recognizable when there is a large amount of fat tissue between the various substrates, while fascia it is difficult to evaluate when there are large connections between the deep fascia and the muscle [14]. The continuity of the aponeurotic fascia around the tendons and nerves can be assessed using both MRI and CT scans. Both of these imaging techniques are also used in evaluating the continuity of retinacula and their respective fasciae, with the delineation between the fascia and retinaculum being based only on the relative increase in thickness. The disadvantages of MRI scans include cost, the time required for image acquisition, increased discomfort for the patient and risk of motion that can cause artifacts, resulting in poor image quality. Moreover, dynamic evaluation of fascia and high-resolution images are not possible with MRI scans as opposed to ultrasound imaging.

Ultrasound (US) imaging is widely used in clinical practice and can be used at a lower cost than other non-invasive methods. Ultrasound scans allow clinicians to analyze fascia at high resolution and to measure the thickness of the various substrates. This is the only instrumental analysis that allows clinicians to view gliding between fascia and muscle or between the various fascial layers [30].

Although ultrasound imaging seems to be the most appropriate technique for studying fascia, there is still a lot of confusion in the literature on how fascia appears on US scans and what the standard reference values are for the various fasciae.

Objective

The objective of this work is to summarize the existing knowledge on morphometric (thickness) and dynamic (strain or motion) US imaging measures of the muscular fascia in healthy human muscles and identify gaps in the literature.

This will help to standardize parameters for fascial gliding imaging measures and define the normal thickness of the muscular fascia in different areas of the body among healthy individuals. It is only by defining these parameters that clinicians will be able to evaluate and compare the pathological conditions of deep fascia.

Methods

Literature search and selection

A state-of-the art review was conducted to address current issues related to a particular topic either to shed light on an area for further research or to offer new perspectives on the subject [19]. An electronic document search using key words and medical subheadings (MeSH) was performed to identify studies published in the following electronic databases: Medline, Scopus and Google Scholar. References obtained from each database were imported and duplicates were eliminated. The following inclusion criteria were determined a priori and were used to screen the articles: (1) full-text publications in English; (2) in vivo studies conducted on the deep fascia of healthy humans; and (3) reporting of original data related to outcomes on morphometric or dynamic measurements. For this study, only the muscular fasciae listed in Terminologia Anatomica were considered. Studies on the iliotibial tract were also included because it is a thickening (or reinforcement) of the fascia lata [53] which is listed in Terminologia Anatomica. Studies on the plantar aponeurosis were also included because this structure is listed under the fasciae of the inferior limb in Terminologia Anatomica. Moreover, the plantar fascia shows functional and morphological characteristics that are typical of aponeurotic fascia: it covers and protects the intrinsic muscles and it is formed by a superficial layer (with fibers arranged longitudinally) and a deep layer (with bundles of collagen fibers with a transverse orientation) [52]. Morphometric measurements referred to fascia thickness and dynamic measurements referred to changes in the position of adjacent layers of the deep fascia (strain) or to changes in the position of the deep fascia in relation to another structure or to a reference point (motion). Articles were excluded if: (1) the data specific to the deep fascia were not reported, and (2) the outcome focused on pathological findings (i.e., eosinophilic fasciitis, necrosis) of the deep fascia. Two independent investigators (NG and CF) were tasked with screening the articles. Disagreements were resolved through consensus.

Data extraction

The following information were extracted from the studies included in the review: main author and year, population (sample size), study design, measurements outcomes and results. A template was used to ensure uniformity of the procedure. Two investigators (NG and CF) were involved in the data extraction process and disagreements were again resolved through consensus.

Quality assessment

Due to the heterogeneity of the research designs and methods used in the studies and to be consistent with the type of review chosen, no formal quality assessment was conducted. However, risks of bias were identified and discussed to help emphasize the strengths and weaknesses of the studies, which enabled the investigators to make an informed review of the selected documents.

Knowledge synthesis

Once again, to be concordant with the proposed type of review, no formal best evidence synthesis was performed. A critical appraisal of what was known was carried out and recommendations for future research were formulated.

Results

The literature search identified 65 articles related to healthy facia in the various databases consulted. After the two investigators read the titles and abstracts, the full text of 32 articles was obtained. Once duplicates ($n=4$) were removed and the articles were read, 20 articles were kept for the review. The reasons for exclusion were as follows: data reported were not specific to the deep fascia or were not related to morphologic or dynamic measurements of the deep fascia ($n=5$), study was based on an animal model ($n=1$) or articles did not report original data ($n=2$).

Ultrasound imaging of the deep fascia by anatomical region

Ultrasound imaging has been used to measure the thickness and the gliding/displacement of the deep fascia in various anatomical regions of the body. Table 1 synthesizes the main data from the relevant studies included in this review.

Based on the data presented in Table 1, one can see that static and/or dynamic US measurements of what the authors defined as the deep fascia were reported for 9 anatomical regions: iliotibial (ITT) tract ($n=6$ studies [9, 18, 20, 23, 55, 57]); plantar fascia ($n=4$ studies [17, 42, 43, 58]); sternocleidomastoid (SCM) and/or scalene ($n=3$ studies [20, 48, 51]); thoracolumbar fascia (TLF) ($n=3$ studies [30, 31, 45]); quadriceps – vastus lateralis (VL) or rectus femoris (RF) ($n=3$ studies [4, 24, 51]); gastrocnemius – medial or

Table 1 Ultrasound outcomes in the evaluation of muscular fascia

References	Transducers: frequencies, scanning plan and location	Outcome: thickness (*T*), displacement (*D*), reliability (*R*)
Iliotibial tract (ITT)		
Goh et al. [18]	8–15 MHz (Sequoia 512, Acuson) and 8–14 MHz (Powervision 6000, Toshiba) linear array; on femoral condyle and condyle	*T*: 1.95 ± 0.3 mm (femoral condyle), 3.4 ± 0.5 mm (tibial condyle)
Gyaran et al. [20]	3–12 MHz linear array (Voluson-i, General Electric Healthcare (GE)), on femoral condyle, 2 cm above the joint line	*T*: 1.10 ± 0.2 mm *R*: intra-operator ICC = 0.71 right side; 0.75 left side
Hyun-sook et al. [23]	5–12 MHz linear array (machine brand not mentioned) on femoral condyle, 2 cm above the joint line	*T*: 1.14 ± 0.4 mm
Condino et al. [9], Turini et al. [55]	3D movement patterns of vector field	*D*: 3D vector field displacement was shown errors: 2.46%(position), 0.81% (orientation)
Wang et al. [57]	12–5 MHz linear array (HDI5000, Philips), transverse axis, probe location not mentioned	*T*: 1.9 ± 0.2 mm
Plantar fascia (PF)		
Gadella et al. [17]	12 MHz linear array (Applio XG, Toshiba), long axis, plantar aspect of the hindfoot, insertion onto the calcaneus	*T*: 3.7 mm (range 2.5–7) male; 3.5 mm (range 1.7–5.1) female
Rathleff et al. [42]	13 MHz linear array (LOGIQe, GE) long axis, probe location as in Gadella et al	*T*: 3.4-4.0 mm *R*: Intra-operator ICC = 0.67–0.77 *R*: Inter-operator ICC = 0.52–0.82
Rios-Diaz et al. [43]	6–15 MHz linear array (LOGICS8, GE), long axis, probe location as in Gadella et al	*T*: 3.2 ± 0.70 mm (range: 2.93–3.51)
Welk et al. [58]	12-MHz linear array (LOGIQe, GE), long axis, probe location as in Gadella et al	*T*: 3.00 mm ± 0.50 mm (walkers), 3.19 ± 0.67 mm (runners)
Sternocleidomastoid (SCM)/scalenus (Sc)		
Harley et al. [21]	17 – 5 MHz linear array (iU22, Philips), long axis, at the middle portion of the muscle belly	*T*: 0.49 ± 0.17^a right side; 0.42 ± 0.09^a left side - sup. border *T*: 0.66 ± 0.18^a right side; 0.65 ± 0.24^a left side - deep border *R*: Intra operator ICC (novice) = 0.49 (sup. border), 0.02 (deep border); Intra-operator ICC (experienced) = 0.70 (sup. border), 0.78 (deep border) *R*: Inter-operator ICC = 0.43 (sup. border), 0.03 (deep border)
Stecco et al. [51]	10 MHz linear array (machine brand not mentioned), long axis, distal end of the SCM	*T*: SCM: 1.11 ± 0.40 mm (right side), 1.07 ± 0.38 mm (left side)
Stecco et al. [48]	5–10 MHz linear array (Aloka Prosound, Hitachi), long axis, distal end of the SCM and midway between mastoid process and first rib for Sc	*T*: SCM: 1.1 mm^b (right and left side)–sup. border T: SCM: 1.1 mm^b (right side), 0.12 mm^b (left side)–deep border *T*: Sc: 1.0 mm^b (right side), 1.6 mm^b (left side)–sup. border *T*: Sc: 1.1 mm^b (right side), 1.8 mm^b (left side)–deep border
Thoracolumbar fascia (TLF)		
Langevin et al. [30]	10 MHz linear array (t3000, Terason), long axis, L2-3 spinal level, 2 cm lateral to the spinous processes	*T*: 3.7 ± 0.04 mm (male); 4.1 ± 0.03 mm (female) *D*: average shearstrain was 62% (SD = 27.2%) among all subjects tested, shear strain was 20%lower in subjects with LBP compared with subjectswithout LBP

Table 1 (continued)

References	Transducers: frequencies, scanning plan and location	Outcome: thickness (*T*), displacement (*D*), reliability (*R*)
Langevin et al. [31]	MHz linear array (t3000, Terason), long axis, L2-L3 spinal level, 2 cm lateral to the spinous processes	*T*: 3 mm (value estimated from histogram, exact mean values not presented)
Schilder et al. [45]	US: not described L3-L4 spinal level, 4 cm lateral to the spinous processes	*T*: 2.1 ± 0.5 mm
Quadriceps: vastus lateral (VL) and rectus femoris (RF)		
Bhansing et al. [4]	5–10 MHz linear array (Zonare Medical Systems) and 5–17 MHz linear array (IU22, Philips), long axis, two-thirds (VL) and ½ (RF) of distance between the anterior–superior iliac spine and upper edge of the patella	*T*: VL: 1.33 ± 0.20 mm *T*: RF: from 1.02 ± 0.16 mm to 1.15 ± 0.18 mm, sup. border and from 1.23 ± 0.17 mm to 1.36 ± 0.19 mm, deep border
Ichikawa et al. [24]	Linear array (EUB-7500; Hitachi), frequency range not mentioned, scanning plan not mentioned	*D*: VL displacement of 28.3 (±4.3) mm for sup. border; 5.2 (±1.0) mm for deep border
Stecco et al. [51]	10 MHz linear array (machine brand not mentioned), long axis, proximal ¼ RF	*T*: RF: 3 fascial layers of deep fascia (right vs left side): superficial (0.54 ± 0.16 vs 0.55 ± 0.18 mm); middle (0.38 ± 0.12 vs 0.38 ± 0.14 mm); deep (0.40 ± 0.10 vs 0.43 ± 0.15 mm)
Gastrocnemius—medial (MG) or lateral heads (LG)		
Cruz et al. [11]	5–10 MHz linear array (Titan; Sonosite), long axis, on themuscle belly of the MG	*D*: MG: 1.50 ± 0.78 mm for mean max angular displacement of the pelvis of 6.55 ± 2.47° in retro-anteversion
Luomala et al. [33]	6–15 MHz linear array (LOGIQ P6, GE), long axis, halfway up the LG	*D*: LG: qualitative assessment of displacement of the superficial, middle and deep layer of the LG fascia
Other muscles: brachioradial fascia (BF), middle deltoid(MD) and rectus abdominus (RA)		
Rozin et al. [44]	5–10 MHz linear array (Titan, Sonosite), long axis, upper part of BF	*T*: BF: 0.75 ± 0.19 mm
Bhansing et al. [4]	5–10 MHz linear array (Zonare Medical Systems) and 5–17 MHz linear array (IU22, Philips), long axis, ¼ of the distance from acromion to lateral epicondyle	*T*: MD: 0.54 ± (0.08) mm − 0.61 ± (0.09) mm
Stecco et al. [51]	10 MHz linear probe, (machine brand not mentioned), transverse axis, 2 cm laterally to umbilicus	*T*: RA: R: 1.69 ± 0.50 mm, L: 1.66 ± 0.39 mm

ICC intraclass correlation coefficient, *sup.* superior, *max* maximal

[a] These data have been rounded to two decimal points in the table and in the manuscript for clarity;

[b] These results were reported in cm in the original article, but we chose to convert to mm in the table and in the manuscript to avoid confusion in interpretation

lateral heads ($n=2$ studies [11, 33]), deltoid ($n=1$ study [4]); brachioradialis ($n=1$ study [44]) and rectus abdominus ($n=1$ study [51]).

Iliotibial (ITT) tract

Four studies including a combined total of 144 healthy participants (80 men, 51 women) reported thickness measures for the ITT [18, 20, 23, 57]. The mean age ranged from 21.3 to 24.7 years for the studies by Gyaran et al. [20], Hyun-Sook et al. [23] and Wang et al. [57], whereas Goh et al. [18] only mentioned the participants' age from 18 to 68 years. The femoral condyle was the probe location for both Hyun-Sook et al. and Gyaran et al., located 2 cm above the lateral joint line. These authors reported similar mean thickness values ranging from 1.10 ± 0.2 to 1.14 ± 0.4 mm. Gyaran et al. also investigated inter-session reliability (one operator, 11 participants, both sides) and intra-class coefficients (ICC) of 0.71 and 0.75, calculated for the right and left ITT respectively. These authors found no relationship between ITT thickness and variables such as age, weight, sex and side dominance.

Goh et al. measured ITT thickness at two separate locations, placing the probe on the lateral femoral condyle without mentioning the distance to the joint line, and then on the tibial condyle. The mean thickness values were 1.95 ± 0.3 mm for the first location and 3.4 ± 0.5 mm for the second location. These authors also investigated the association between ITT thickness and age and reported a trend toward decreasing ITT thickness measured at the femoral condyle with the increasing age of participants ($r=0.50$; 95% CI [− 0.73 to − 0.18] for the left side and r = -0.42; 95% CI [− 0.678 to − 0.071] for the right side). The mean ITT thickness value reported by Wang et al. was similar to that documented by Goh et al. i.e., 1.9 ± 0.2 mm, and the probe location was not detailed explicitly.

The two other articles were written by the same group of authors and were related to displacement measurements [9, 55]. The authors' work presented the development of a semi-automatic method that focused on 3D displacement of adjacent deep fascial layers of the ITT during an isometric voluntary contraction of the knee extensor muscles performed by 2 healthy males (aged 29 and 35 years). Displacement of the fascial layers were demonstrated by vector changes in position and orientation and measurement errors of the model were 2.46% for position and 0.81% for orientation.

Plantar fascia

The four studies included a combined total of 135 healthy participants, with a mean age range of 23–45 years, and provided thickness value data for a total of 50 men and 62 women (gender was not mentioned in Rios–Diaz study) [17, 42, 43, 58]. The probe was positioned on the long axis. The mean thickness values reported ranged from 3.0 to 4.0 mm. Two of the studies [42, 43] also documented intra- and inter-operator reliability, with intra-class coefficients (ICC) from 0.67 to 0.77 for intra-operator reliability, and from 0.52 to 0.82 for inter-operator reliability. Moreover, Rathleff et al. observed that inter-operator reliability was higher when both operators measured the same scan (e.g., both measured the scans of operator 1) than when they measured their respective scans.

Sternocleidomastoid/scalene

Three studies [20, 48, 51] quantified the deep fascia of the SCM, including a combined total of 57 healthy participants (22 men and 35 women) with a mean age of 26.2–38.9 years. The probe was positioned on the long axis at the distal end of the SCM in Stecco et al. [51], and on the middle portion of the muscle belly in Harley [20]. In all studies, the deep fascia was measured on both sides of the muscle belly, that is, on the superior and deep border of the SCM (c.f. superior and inferior border of the muscle, in reference to the US image). Mean thickness values for the deep fascia of the superficial border of the SCM muscle ranged from 0.49 to 1.11 mm, while those for the deeper border ranged from 0.66 to 1.1 mm. Harley examined intra-and inter-operator reliability (one experienced operator and one novice operator participated to this study). For the superior border of the deep fascia, the intra operator ICC was 0.70 with a 95% CI of [0.38–0.87] for the experienced operator and 0.49 with a 95% CI of [0.08–0.76] for the novice operator. For the deep border of the SCM fascia ICC were as follows: 0.78 with a 95% CI of [0.53–0.91] for the experienced operator and 0.12 with a 95% CI of [0.33–0.52] for the novice operator. In terms of inter-operator reliability, ICCs for the left and right side ranged from 0.03 (superficial border) to 0.43 (deep border). The authors also performed an extraction measurement error reliability analysis by comparing the measurements obtained by both operators on the same US image. Intra-operator ICCs were 'near perfect' for all structures (all ICC's > 0.965). The inter-operator ICC for the fascia on the superficial border was 0.63, with a 95% CI of 0.04 to 0.89 and 0.76, with a 95% CI of 0.30–0.94 for fascia on the deep border.

Thickness of the fascia on the superficial and deep borders of the scalenus medius muscle was reported by Stecco et al. ($n=25$ healthy participants, 10 men and 15 women, mean age = 38.9) [48]. The probe was positioned on the long axis, midway between the mastoid process and the first rib. For the fascia on the superficial border, the mean thickness values were 1.6 and 1.0 mm for the left and right side respectively, whereas for the fascia on the deep border, the mean values were 1.8 mm for left side and 1.1 for the right side.

Thoracolumbar fascia

Data on US measurements of the thoracolumbar fascia (TLF) were reported in three studies [30, 31, 45], which included 109 healthy participants (56 men and 59 women) with a mean age of 24.0–41.8 years. In both of the studies by Langevin et al., the probe was placed on the long axis, 2 cm lateral to the spinous processes at the level of the L2–3 interspace, whereas in the study by Schilder et al. [45], the probe was located 4 cm lateral to the spinous processes and at L3–L4. In the 2009 study by Langevin et al. [31], the deep fascia corresponded to the perimuscular zone represented by an echogenic layered structure close to the muscle, with the thickness of the TLF among healthy participants measuring around 3 mm (value estimated from an histogram; exact mean values not presented; data from men and women were combined). In the 2011 study [30], the authors reported thickness values of 3.7 ± 0.04 mm for men and 4.1 ± 0.03 mm for women. In the Schilder et al. study, the estimated mean thickness was 2.1 ± 0.5 mm.

Langevin et al. used dynamic US recording and cross-correlation techniques to estimate the displacement of the aponeurosis of the erector spinae (deeper layer of the TLF) and the aponeurosis that merge together to form the remainder of the TLF (more superficial layer of the TLF) in relation to a point of reference. The data were recorded during passive trunk flexion movements and shear strain was derived from these data and expressed as a percentage. The authors demonstrated that for the healthy participants, shear strain was 70.2 ± 3.6%, which was about 20% higher than for participants who had chronic low back pain. Overall, males had significantly lower shear strain than females ($p = 0.02$) and significant correlations were found in men between TLF shear strain and perimuscular connective tissue thickness ($r = -0.45$, $p < 0.001$).

Quadriceps (VL and RF)

Two studies reported data for the VL (vastus lateral) muscle [4, 24] and two for the RF (rectus femoris) muscle [4, 51]. Bhansing et al. measured VL fascia thickness on a sample of 54 healthy volunteers (27 men and 27 women, age 21–86 years) [4]. The probe was placed at two-thirds from the distance between the anterior–superior iliac spine and the upper edge of the patella, on the longitudinal axis. The fascia between the subcutaneous tissue and muscle fibers was defined as superficial fascia whereas the fascia between the muscle and the adjacent muscle as deep fascia. These authors used different measurement protocols (i.e., mean measurements at 0.25-cm interval; mean measurement of the 3 thickest measurements and mean measurement of the 6 thickest measurements) and reported the following results: the mean thickness of the superficial fascia ranged from 1.28 (± 0.30) mm to 1.46 (± 0.36) mm and from 1.33 (± 0.20) mm to 1.43 (± 0.23) mm for the deep fascia.

The other study on VL fascia US measurement focused on motion [24]. Ichikawa et al. measured the change in position between the superficial layer of deep fascia (defined by the fascia located between the subcutaneous tissue and vastus lateralis muscle) and the deep layer of the deep fascia (defined by the fascia located between VL and vastus intermedius) according to a point of reference during knee flexion movement. The location of the probe was not mentioned. This study by Ichikawa et al. involved 12 healthy adult males between 22 and 34 years of age. The authors showed that as the knee flexed, mean deep fascia displacement was 5.2 (± 1.0) mm and mean superficial fascia displacement was 28.3 (± 4.3) mm. This displacement increased for both superficial and deep fasciae following myofascial release therapy.

For the rectus femoris (RF), Bhansing et al. [4] used different measurement protocols in the same healthy population as described for the VL (see above). The probe was placed on the RF, halfway between the anterior superior iliac spine and the upper edge of the patella. The authors reported RF mean thickness values ranging from 1.02 (0.16) to 1.15(0.18) mm for the superficial deep fascia and from 1.23 (0.17) to 1.36 (0.19) mm for the deep fascia. Stecco et al. [51] measured the thickness of the superficial, middle and deep layers that composed the deep fascia of the RF on 22 participants (7 men, 15 women; mean age: 37.5 years). The probe transducer was positioned on the proximal quarter of the rectus femoralis (fascia lata). The thickness of each fascial layer was as follows (right *vs* left side): superficial (0.54 ± 0.16 vs 0.55 ± 0.18 mm); middle (0.38 ± 0.12 vs 0.38 ± 0.14 mm); deep (0.40 ± 0.10 vs 0.43 ± 0.15 mm).

Gastrocnemius—medial or lateral heads

The two studies reporting data on the fascia of the gastrocnemius focused on dynamic measurements [11, 33]. In one case study involving a 40-year-old man, Luomala et al. [33] investigated the change of position of the deep fascia layers of the lateral gastrocnemius before and after Fascial Manipulation© was applied to the area. For these authors, the deep fascia was defined as a structure composed of 2–3 layers of parallel bundles of collagen fibers. Each layer is separated from the adjacent one by a thin layer of loose connective tissue. The probe was placed halfway up the calf, positioned slightly towards the peroneus muscle. From a visual interpretation of the US image, the authors observed a change in the position of all layers and concluded that the greatest displacement appears to occur in the deepest layer.

Cruz-Montecinos et al. [11] evaluated change in position of the medial gastrocnemius deep fascia during cyclic retro-anteroversion movement of the pelvis in a sample of

17 healthy men (mean age: 22.8 ± 1.8 years). The authors defined deep fascia as a distinguishable connective tissue surrounding and splitting the muscle groups. The probe was positioned on the muscle belly of the medial gastrocnemius, on the longitudinal axis. The mean of the maximal change in position of the fascia was 1.50 ± 0.78 mm for a mean maximal angular displacement of the pelvis of 6.55 ± 2.47° during retro–anteversion movements.

Other muscles

Thickness data values were reported for three other muscles. Bhansing et al. [4] measured fascia thickness of the middle deltoid on a sample of 54 healthy volunteers (27 men and 27 women, age 21–86 years). The fascia between subcutaneous tissue and the muscle fibers was defined as superficial fascia and the fascia between the muscle and the adjacent muscle as deep fascia. The probe was placed a quarter of the distance from the acromion to the lateral epicondyle. Thickness values were obtained from three different measurement protocols (for details on these protocols see results for the VL fascia) and ranged from 0.54 ± (0.08) to 0.61± (0.09) mm.

Rozin et al. [44] measured the brachioradial fascia (superior border of the muscle) in 10 healthy men (men age was 36.7 ± 8.3 years). The probe was placed on the longitudinal axis. The brachioradial fascia had a mean thickness of 0.75 ± 0.19 mm.

Stecco et al. [51] measured the fascia of the rectus abdominus in 22 healthy volunteer participants (7 men and 15 women; mean age: 37.5 years). The probe was positioned on the transverse axis, 2 cm laterally to umbilicus. The authors defined the deep fascia as 2–3 layers of densely packed collagen fibers with a few scattered elastic fibers, with a layer of loose connective tissue between these layers. The thickness of the rectus abdominus fascia was 1.66 ± 0.39 and 1.69 ± 0.50 mm for the left and right side respectively.

Discussion

Deep fascia thickness measurements

To our knowledge, this review is the first to focus on morphometric and dynamic US imaging measurements of the muscular fascia for different areas of the body in healthy individuals. Attempting to synthetize the data on healthy fascia constitutes an initial step towards a better understanding and interpretation of what should be considered normal in terms of the thickness and fascial displacement/gliding. Fascia is seen on ultrasound images as a linear hyperechoic line with boundaries that are often easily identifiable due to the adjacent hypoechoic band of muscular tissue [48]. Although US imaging has increased in popularity in clinical practice, the important observations made in this review reveal that there are still only a few studies that focus on muscular fascia measurement, many nomenclatures are used to describe fasciae and there is high heterogeneity in the methods used to collect data and measure thickness and displacement. The ITT and plantar fasciae are the most often studied muscular fasciae whereas there is paucity of studies on the fascia related to other muscles in the body. The greater interest in ITT and plantar fasciae might be related to the high prevalence of symptoms or pathologies reported for these fascial structures such as ITT syndrome, plantar fasciitis, plantar fascia necrosis to name a few. However, there is a growing body of literature suggesting that the fascia might be the cause of pain and/or other symptoms in other musculoskeletal disorders such as non-specific low back pain [30, 31], carpal tunnel syndrome [41] and fibromyalgia [32]. Ultrasound imaging of the muscular fascial system could prove useful in improving our understanding of these very complex conditions, but first we need to find greater homogeneity and fill in the existing gaps.

ITT

For the ITT, the thickness values ranged from 1.10 to 3.34 mm. However, it is important to mention that the higher values corresponded to the measurements taken at the level of the lateral tibial condyle in Goh et al. [18]. When considering the measures taken at the level of the femoral condyle (2 cm above the joint line), the thickness value was close to those reported by other authors who used the same probe location and similar to the thickness values measured on cadaver samples [50]. This highlights the importance of standardizing the probe location. Finally, Goh et al. [18] reported a negative correlation with age (i.e., ITT getting thinner with age), in accordance with previous literature in animals [26] and humans [7, 12, 25, 35]. Conversely, Gyaran et al. [20] showed no correlation between thickness and aging, although the sample was mainly composed of young individuals.

In all 4 studies, participants were positioned supine. For ITT thickness measurements, this position with the probe placed 2 cm above the femoral condyle might provide the most consistent measures. Using this measurement protocol, Gyaran et al. [20] reported good intra-operator reliability with an ICC of 0.75 and 0.71 for the right and left ITT respectively, despite the small sample of participants ($n = 11$).

Plantar fascia

Plantar fascia thickness measurements ranged from 3 to 4 mm. The position of the probe and landmarks for thickness measurements (i.e., anterior aspect of the inferior border of the calcaneus) were the same in all studies. However, the position of the participants was different in each study. Welk et al. [58] were the only ones to evaluate participants during prolonged sitting with the knee extended and the ankle in neutral position. Knowing that the fasciae of the lower spine, pelvis, upper and lower leg and foot are all interconnected [60], this position might have been the one that put the greatest tension on the plantar fascia [46]. This may explain why mean thickness values reported by these authors were in the lower range. Although the other studies took measurements with patients in a prone position, different positions were reported: (1) knee flexed to 90° with ankle in neutral position [43]; (2) knee extended, ankle dorsiflexed and toes extended [42]; and (3) knee extended with the foot hanging freely over the end of a bed [17]. Once again, different ankle and toe positions can put tension of the plantar fascia and this have an impact on morphometric measurements. Moreover, intra- and inter-operator reliability was documented in two studies. Rios-Diaz et al. [43] found that intra-operator reliability was slightly better than inter-operator reliability, while Rathleff at al [42]. reported better inter-operator reliability than intra-operator reliability. These authors assessed three different measurement methods: one single measurement, mean value of two measurements or mean value of three measurements. The three measurement methods improved both intra- and inter-operator reliability, but inter-operator reliability remained higher, with the ICC reaching 0.82.

With this evidence, the present review encourages clinicians to measure plantar fascia thickness at the anterior aspect of the inferior border and to calculate the mean value for three measurements. It is nevertheless important to standardize the patient position.

SCM

The mean thickness values for SCM fascia ranged from 0.49 to 1.2 mm. Two out of the three studies targeting this fascial structure were from the same group (Stecco et al. [48, 51]) and reported similar thickness values. The thickness values in the study by Harley [21] were close to less than twice those reported by Stecco. The study by Harley [21] used the same definition for deep fascia as Stecco et al. [51], being defined as a multi-layered structure formed by two to three layers of densely packed collagen fibers with a layer of loose connective tissue between these fibrous layers. But as Harley [21] mentioned, the discrepancy in the thickness measures might be related to the difficulty the operators experienced in visualizing the fascial boundaries or to the differences in probe's location (midpoint of the SCM in Harley's study, and distal quarter of the muscle in Stecco's studies), or to the small sample size ($n = 10$) in Harley's study.

TLF

The TLF was the focus of three studies. Two studies were conducted by Langevin et al. [30, 31] with a large sample size. Since the exact mean thickness value was not reported by Langevin et al. in 2009, it is difficult to conclude on a normal reference value. However, it is worth mentioning that these authors were the first to report that people with non-specific low back pain (LBP) had, on average, 25% greater perimuscular connective tissue thickness than healthy people. In our opinion, the procedure used by these authors to measure TLF thickness was very rigorous. In fact, it is detailed enough to be used in future research to study whether a given intervention can restore the morphometry of the TLF back to normal values and to study the relationship between these morphometric changes and symptoms.

Schilder et al. [45] reported lower thickness values compared to Langevin et al. (2011), but took their measurements at a lower spinal level. The subcutaneous gluteal fat pad can begin at more caudal location and this can change the angle between the skin surface and the TLF and induce an artefact on the images [31]. However, it is important to mention that Schilder's primary objective was not to measure TLF thickness but to demonstrate that the TLF is the deep tissue in the back that is the most sensitive to chemical stimulation, thus highlighting its role in nonspecific LBP.

RF and other muscles

Two studies reported thickness values for the RF [4, 51], with results ranging from 1.33 mm for Bhansing to approximately 1.66 for Stecco, provided that we add up all the thickness values for all the layers, because not only were thickness measures for each muscular fascia layer reported but also for the loose connective tissue that lies in between. Measuring the loose connective tissue might be clinically relevant because it would support the existence of the concept of fascial densification [40]. Fascial densification has been described as an alteration of the quantity or quality of these loose connective tissue components that may change the viscosity and therefore, the viscoelastic properties of the fascial tissue [10]. This situation does not create a macroscopic alteration of the morphology of the fascia tissue that can be appreciated with imaging, like fibrosis does for example. Densification may be associated with myofascial pain syndrome [47]. The difference in the thickness reported for the RF might be attributable to probe location, given that Stecco's position was more proximal. As regards the other studies reporting thickness measurements for the other areas of the body (scalenius, VL, deltoid, brachioradial, and rectus abdominus), although the studies provided interesting results and original data, more research is required to make recommendations on measurement procedures and draw conclusions on reference values.

Dynamic deep fascia measurements

Ultrasound morphometric measures like thickness has proven useful in supporting the diagnosis of some pathologies affecting fascia like plantar fasciitis and monitoring changes following rehabilitation interventions. However, assessment of fascial mobility could provide crucial information about fascial dysfunctions and, to a certain point, help to understand myofascial pain and movement disorders. In fact, studies have shown the muscular fascia is innervated by nociceptive free nerve endings suggesting a potential role of the fascia in the etiology of painful conditions like non-specific LBP [49, 59]. Moreover, it is now well recognized that the muscular fascia plays a major role in movement perception and coordination, and in the transmission of forces [39]. Therefore, any restriction in the mobility of the fascia or in the gliding of its layers can alter afferent input from mechanoreceptors or can cause reorientation of internal force vectors that will result in movement disorders.

This review revealed that there is a paucity of studies on dynamic measurements of the muscular fascia. These measurements were reported for the fascia of four areas of the body: TLF [30], ITT (thicker part of the fascia lata) [9, 55], muscular fascia of the VL [24] and muscular fascia of the lateral gastrocnemius [11]. Langevin et al. [30] first aimed at evaluating TLF "shear strain" defined as the relative displacement of the TLF layers, estimated during passive trunk flexion using innovative cross correlation methods. These authors not only documented TLF shear strain for the first time, but also found that participants with LBP had reduced TLF shear strain in the lumbar region with respect to asymptomatic participants. This method is of great interest, but questions remain as to whether the authors measured the displacement between adjacent layers of the same tissue (i.e. the TLF) or between the TLF and the perimysium of the erector spinae, which are two distinct tissues. Therefore, the definition of TLF shear strain provided by these authors might not be appropriate.

Ichikawa et al. [24] demonstrated that there was a change in the position of the "superficial" and "deep" layers of muscular fasciae of the VL during knee flexion movement after a fascial release intervention. This particular study thus measured the displacement of two points (relative to a reference point) of the epimysium of the VL. The use of the "superficial" and "deep" to describe the layers of the muscular fascia is confusing and should be reserved for motion measurements of the adjacent layers of the same muscular fascia.

Luomala et al. [33] demonstrated that the position of the 3 layers of the muscular fascia above the lateral gastrocnemius relative to a reference point had changed following a Fascial Manipulation© treatment. However, this study included only one participant and qualitative visual interpretation of the image was used to estimate the displacement. Condino et al. [9] and Turini et al. [55] developed and improved a method that quantified the 3D motion of salient ITT fascial features identified in a pair of 3D musculoskeletal US images during an isometric contraction of the knee extensor muscles. This group was the first to quantify changes in the position and orientation of the different fascial layers in 3D. Their studies, like the one performed by Langevin et al. [30], are very promising but highly qualified human resources and complex software programs are required to process and interpret that data.

Heterogeneity of the studies

US imaging is a useful technique to conduct dynamic measurements and thickness evaluations of muscular fascia. Since this review's aim was to summarize key challenges that need to be addressed to achieve an homogeneous evaluation of the muscular fascia, we can summarize the following fundamental points as follows:

1. *Terminology* There is a need for consensus on the nomenclature of muscular fascia to develop methods that will homogeneously measure the same concepts. For example, some authors used the term superficial fascia, while it was clear that they were referring more to the fascia of the superior border of a muscle (in reference to the US image). This can be confusing because the superficial fascia is the membranous layer of the hypodermis (or *tela subcutanea*) (Terminologia Anatomica) [16]. Consequently, it is functionally, morphologically and histologically different from muscular fascia.
2. *Fascial properties that need to be evaluated* Thickness, gliding, echogenicity, stiffness. This review focussed on the first two properties. We can assume that US imaging of fascia other than plantar fascia is considered a new field. Fasciae in other areas have a more complex structure and more research is needed to differentiate tissue types and gain a better knowledge on US setting adjustment that may best optimize visibility.
3. *Position of the probe* The US probe can be positioned along the longitudinal axis, with the long axis of the probe aligned with the long axis of the structure, or along the transverse axis, or with the long axis of the probe perpendicular to the long axis of the structure. Different measures are obviously obtained with different probe positions, thus encountering the tissue's anisotropy.
4. *Position of the patient* Determining a specific standardized patient position is necessary in order to properly analyze a specific area of the body. This would allow

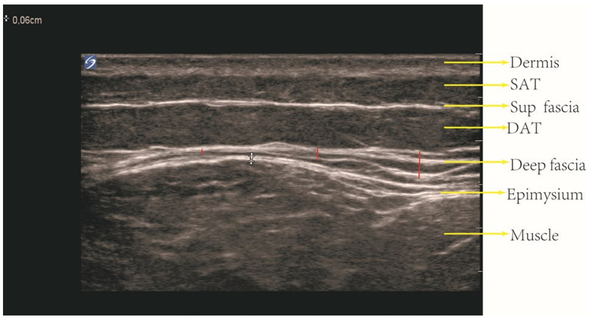

Fig. 1 The importance of the number of US measurements of deep fascial thickness: different measurements (in red) at various specific points can result in different mean values. *SAT* superficial adipose tissue, *DAT* deep adipose tissue, *Sup fascia* superficial fascia

clinicians to compare the various studies and different measurements;

5. *Inter-operator reliability* Different operators may obtain different mean values, especially when novice operators are involved.
6. *Intra-operator reliability* An operator's ability may improve with experience; therefore, the correlation between time-based assessments may be reduced.
7. Number of measurements and mean values (see Fig. 1 below). More measurements on the same deep fascia in the same body region are necessary because the fascia is a dynamic type of tissue and under the influence of various. In some cases, for example, the deep fascia may appear adherent to the superficial fascia, resulting in a thicker measurement. To avoid these errors, it is crucial to identify the correct tissue and to take few measurements to obtain a mean value.
8. Necessity to develop a computerized software program for evaluating fascial gliding: Without this type of program, the functional evaluation of the deep fascia is impossible due to the complexity, time required and inapplicability in clinical practice. Moreover, when measuring displacement, it should be clear whether displacement of the deep fascia itself or the displacement of its layers is being measured. The first case reflects the mobility of the whole tissue whereas the second reflects changes occurring inside the tissue.
9. The last but certainly not the least point refers to the fact that the US imaging studies included in this review have provided measurements of "interfaces" and yet, no correlation have been established between anatomy and US imaging measurements.

Conclusions

US imaging is a readily available, portable, and inexpensive imaging modality: The low cost, real time imaging, and its ability to be used as a guide for interventional procedures make this imaging method ideal for most musculoskeletal clinicians, suitable to complement physical examination and indispensable for evaluating treatment outcomes. However, a consensus on the definition of the muscular fascia and on measurement methods should be reached among the fascia research community. Finally, the small number of studies reviewed clearly reveals that muscular fascial measurement is a new field. The heterogeneity of the methods makes it so that for most of the body locations, the present review did not allow us to establish (1) normal reference values for muscular fascia thickness and (2) strong recommendations about protocols. Identifying the discrepancies and gaps in the existing literature and establishing the definition of common guidelines is an important first step in shedding light on muscular fascia measurements before entering the field of myofascial disorders.

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