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Diagnostic Methods

Diagnostic ultrasound assessment of deep fascia sliding mobility *in vivo*: A scoping review – Part 2: Femoral and crural fasciae

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ABSTRACT

Background: Failure of fascial sliding may occur in cases of excessive or inappropriate use, trauma, or surgery, resulting in local inflammation, pain, sensitization, and potential dysfunction. Therefore, the mechanical properties of fascial tissues, including their mobility, have been evaluated *in vivo* by ultrasound (US) imaging. However, this seems to be a method that is not yet properly standardized nor validated.

Objectives: To identify, synthesize, and collate the critical methodological principles that have been described in the literature for US evaluation of deep fascia sliding mobility *in vivo* in humans.

Methods: A systematic literature search was conducted on ScienceDirect, PubMed (Medline), Web of Science and B-On databases, according to the PRISMA Extension for Scoping Reviews (PRISMA-ScR) guidelines. The OCEBM LoE was used to evaluate the level of evidence of each study.

Results: From a total of 104 full-text articles retrieved and assessed for eligibility, 18 papers were included that evaluate the deep fasciae of the thoracolumbar ($n = 4$), abdominal ($n = 7$), femoral ($n = 4$) and crural ($n = 3$) regions. These studies addressed issues concerning either diagnosis ($n = 11$) or treatment benefits ($n = 7$) and presented levels of evidence ranging from II to IV. Various terms were used to describe the outcome measures representing fascial sliding. Also, different procedures to induce fascial sliding, positioning of the individuals being assessed, and features of US devices were used. The US analysis methods included the comparison of start and end frames and the use of cross-correlation software techniques through automated tracking algorithms. These methods had proven to be reliable to measure sliding between TLF, TrA muscle-fascia junctions, fascia lata, and crural fascia, and the adjacent epimysial fascia. However, the papers presented heterogeneous terminologies, research questions, populations, and methodologies.

This two-part paper reviews the evidence obtained for the thoracolumbar and abdominal fasciae (Part 1) and for the femoral and crural fasciae (Part 2).

Conclusion: The US methods used to evaluate deep fascia sliding mobility *in vivo* in humans include the comparison of start and end frames and the use of cross-correlation software techniques through automated tracking algorithms. These seem reliable methods to measure sliding of some fasciae, but more studies need to be systematized to confirm their reliability for others. Moreover, specific standardized protocols are needed to assess each anatomical region as well as study if age, sex-related characteristics, body composition, or specific clinical conditions influence US results.

1. Introduction

This is the second part of this two-part review. In Part 1 we concentrated on the evidence obtained for the thoracolumbar and abdominal fasciae. In Part 2 the aim is to identify, synthesize and

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Table 1
Methodological US imaging of the femoral deep fascial sliding.

US MACHINE	IMAGING MODE	TRANSDUCER					SUBJECTS POSITION	OUTCOME MEASURE(S)	RELIABILITY	PROCEDURES USED TO INDUCE FASCIAL SLIDING	FASCIAL SLIDING ANALYSIS METHOD
		Array type	Freq. (MHz)	Depth (cm)	Location	Handling					
Langevin et al. (2007)											
GE System Five, Vingmed	B-mode Elastography	Linear	10	4	18 cm superior to the middle of the superior edge of the patella	Manual	NS	Tissue displacement (during needle rotation)	NA	Passive robotic acupuncture needling	Cross-correlation software techniques (automated tracking)
Fox et al. (2014)											
Terason 3000; Teratech Corporation, Burlington, MA	B-mode Elastography	Linear	10–12	NS	(1) between RF and VL muscles, 15 cm rostral to the patella (2) over the RF belly, 2 cm medial to place (1)	Fixing device	NS	Tissue displacement (axial/lateral); Shear strain (axial/lateral)	NA	Passive robotic acupuncture needling	Cross-correlation software techniques (automated tracking)
Ichikawa et al. (2015)											
EUB-7500; Hitachi Medical Corporation, Tokyo, Japan	B-mode	Linear	NS	NS	Midway between the greater trochanter and lateral epicondyle of the femur	Manual	Lateral decubitus	Fascial gliding motion	Intra-rater: - Minimal detectable change >95%	Myofascial release; Hot pack therapy + passive knee extension (0°-45°)	Start and end frames comparison
(**Condino et al., 2015a**)											
Philips iU22; Philips/ATL, Bothell, WA, USA	B-mode (3D)	Linear	5–13	NS	Midway between the greater trochanter and lateral epicondyle of the femur	Fixing device	Supine-lying	Fascial mobility	Automatic validation process to evaluate the reliability of feature matches	Isometric knee extension	Cross-correlation software techniques (3D automated tracking – block matching algorithm)

Legend – US: ultrasound; ICC: Intraclass correlation coefficient; Freq.: frequencies; NS: not stated; NA: not available; RF: rectus femoris; VL: vastus lateralis.

collate the key methodological principles that have been described in the literature for US evaluation of femoral and crural fasciae deep fascia sliding mobility in humans *in vivo*, and to analyze the reliability of such principles. Particularly, the review aims at identifying and charting the examined fasciae and the US equipment characteristics and parameters used; documenting the methodological procedures implemented to assess deep fasciae mobility through US measurements; reporting the reliability assessment of the US measurements whenever possible; and determining the level of evidence supporting the use of US imaging to quantify fascial sliding.

2. Methods

The methods used for this review are detailed in Part 1.

A global overview of the selected studies is presented in Table 1, including general data such as identification, demographic characteristics, level of evidence (LoE) (OCEBM Levels of Evidence Working Group et al., 2011), study type assessment (using the "decision algorithm to help define study designs" (Peinemann and Kleijnen, 2015)), body region, and studied fascia.

For each region, a table was designed to collect the methodological information consisting of the US device characteristics (brand and transducer characteristics), the US imaging procedures (imaging mode, acquisition frequency and depth, subjects positioning, transducer's location, and standardizing procedures), different fascial sliding outcome measure(s) used across the papers, the description of reliability analysis for the employed US measurements, the procedures used to induce fascial sliding, and the methods used for fascial sliding analysis.

3. Results

3.1. Selection of sources of evidence

The systematic database search (last run on April 14, 2018) yielded 4282 records. After removal of duplicates, the title and abstract of the remaining 3091 articles were screened. A total of 104 full-text articles were retrieved and assessed for eligibility. Of these, 86 were excluded for the following reasons: 37 did not perform US evaluation of fascial sliding, 19 did not use a sample of humans *in vivo*, 20 did not study deep fasciae (muscular fasciae), 7 were review articles, 1 full-text was not accessible, 1 was a descriptive documentary, and 1 was a pre-clinical study. Therefore, 18 studies were considered for review and grouped into four sections according to the anatomical regions analyzed. Results of the literature search, screening, and selection processes are summarized in the PRISMA diagram (Moher D, Liberati A, Tetzlaff J, 2009) in Fig. 1.

3.2. Synthesis of results

Table 1 shows the general characteristics of the articles included in the current review; Tables 2 and 3 group the methodological data from the studies of the femoral (n = 4) and crural (n = 3) regions.

Study designs, levels of evidence and sample characteristics are globally presented in Part 1 of this review.

3.2.1. Studied fasciae

Four studies analyzed the sliding of the anterolateral fasciae of the thigh (Condino et al., 2015; Fox et al., 2014; Ichikawa et al., 2015;

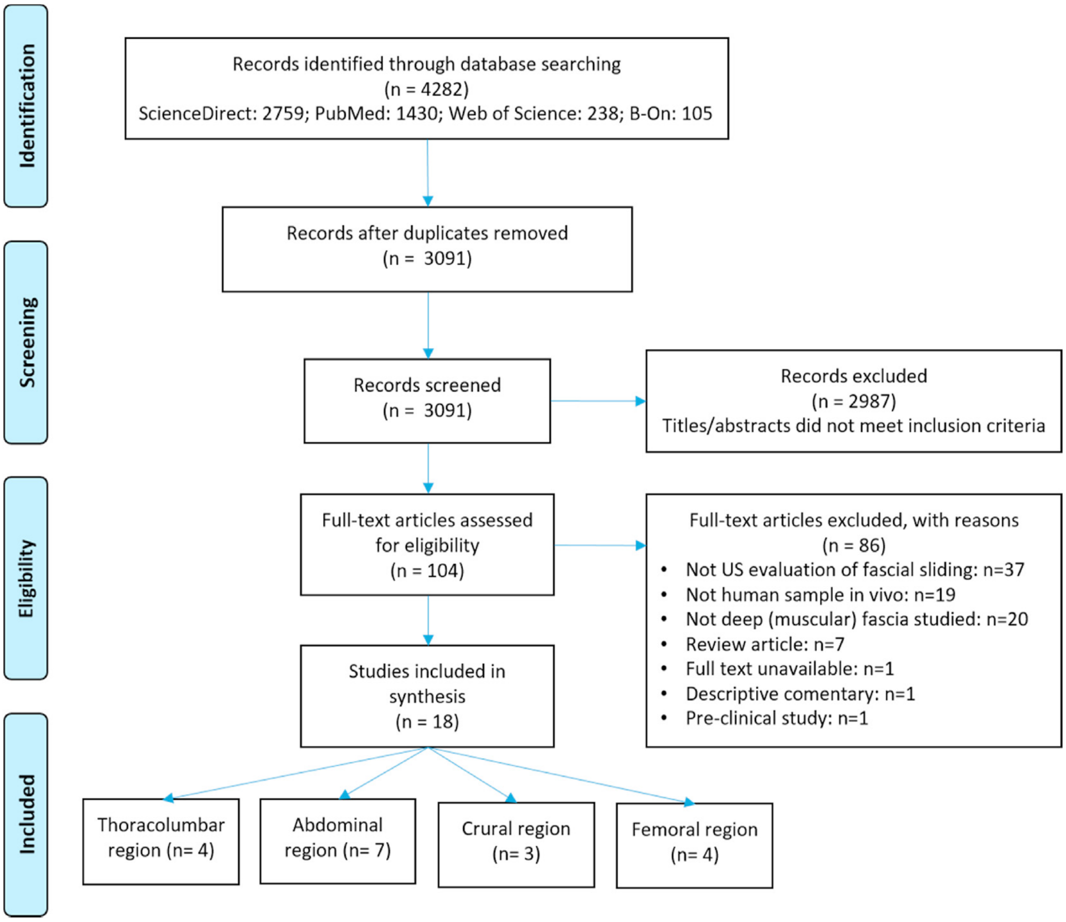

Fig. 1. PRISMA flow diagram of studies identified, screened, selected and included in the review.

Table 2
Methodological US imaging of the crural deep fascial sliding.

US MACHINE	IMAGING MODE	TRANSDUCER					SUBJECTS POSITION	OUTCOME MEASURE(S)	RELIABILITY	PROCEDURES USED TO INDUCE FASCIAL SLIDING	FASCIAL SLIDING ANALYSIS METHOD
		Array type	Freq. (MHz)	Depth (cm)	Location	Handling					
Luomala et al. (2014)											
GE Healthcare's LOGIQ P6	B-mode	Linear	9–15	NS	(1) gastrocnemius lateral part, halfway up the calf, towards the peroneus muscle (2) medial to the biceps femoris, midway on thigh	Manual	Prone-lying	Fascial gliding	NA	Fascial Manipulation® + active, maximal dorsi & plantar flexion	Start and end frames comparison
Cruz-Montecinos et al. (2015)											
SonoSite TITAN®; Sonosite, Bothell, WA, USA	B-mode	Linear	5–10	3.9	On the muscle belly of the medial gastrocnemius on the dominant limb	Fixing device	Siting	Fascial displacement	Intra-rater: ICC = 0.903 Manual tracking VS LKP tracking: - ICC = 0.973 - average difference between methods < 0.95%	Active pelvic anteversion (start at maximum retroversion)	Cross-correlation software techniques (automatic tracking)
Cruz-Montecinos et al. (2016)											
SonoSite TITAN®; Sonosite, Bothell, WA, USA	B-mode	Linear	5–10	3.9	On the muscle belly of the medial gastrocnemius on the dominant limb	Fixing device	Siting	Fascial displacement	NA	Maximal active cervical spine flexion (start at neutral position)	Cross-correlation software techniques (automatic tracking)

Legend – US: ultrasound; ICC: Intraclass correlation coefficient; Freq.: frequencies; NS: not stated; NA: not available.

Langevin et al., 2007) – the fascia lata and the epimysial fascia of the quadriceps muscle, particularly the VL fascia (Ichikawa et al., 2015). For the crural region, the research included three studies that approached the mobility of the crural fascia and the gastrocnemius epimysial fascia (Cruz-Montecinos et al, 2015, 2016; Luomala et al., 2014).

3.2.2. US equipment characteristics

Several US devices equipped with linear or curvilinear array transducers, with distinct central frequencies and operating in B-mode, 3D B-mode or B-mode with elastography were used across the included studies.

The femoral (Condino et al., 2015; Fox et al., 2014; Ichikawa et al., 2015; Langevin et al., 2007) and crural (Cruz-Montecinos et al, 2015, 2016; Luomala et al., 2014) regions were always assessed with linear array transducers.

Most articles presented the US transducer frequency ranges, which overall varied from 4 MHz to 15 MHz. However, specific acquisition frequencies were rarely reported.

The US acquisition depth data were also scarce. A specific acquisition depth of 4 cm was reported in one study evaluating the anterior thigh perimuscular fascia (Langevin et al., 2007). For the crural region fasciae, Cruz-Montecinos et al. (2015, 2016) described acquisition depths of 39 mm in both their studies (Cruz-Montecinos et al, 2015, 2016).

The available data revealed that B-mode was the imaging mode employed in most of the studies (Cruz-Montecinos et al, 2015, 2016; Ichikawa et al., 2015; Luomala et al., 2014). 3D B-mode (Condino et al., 2015) and B-mode with elastography (Fox et al., 2014; Langevin et al., 2007) were also used to explore fascial sliding of the femoral region fasciae, while the crural region fasciae were explored with standard B-mode only.

3.2.3. Subjects positioning and procedures to induce fascial sliding mobility

The subjects positioning depended on the procedure used to induce the fascial layers' mobility.

The participants were positioned in lateral decubitus (Ichikawa et al., 2015) or supine (Condino et al., 2015) to assess the femoral region fasciae; 2 studies (Fox et al., 2014; Langevin et al., 2007) did not specify the positioning, though it is possible to presume that the participants were supine-lying. The procedures used to induce the fascial layers' mobility included passive treatment techniques (myofascial release and hot pack therapy) combined with passive knee flexion movement for VL deep fascia (Ichikawa et al., 2015), robotic needling to evaluate the anterior thigh perimuscular fascia (Fox et al., 2014; Langevin et al., 2007), and active isometric knee extension to study the fascia lata mobility (Condino et al., 2015).

In the studies of the crural region fasciae, the participants were analyzed in a sitting (Cruz-Montecinos et al, 2015, 2016) or prone-lying position (Luomala et al., 2014). The procedures used to induce fascial sliding included "local" active dorsi- and plantar-flexion movements combined with treatment procedures (Fascial Manipulation™) (Luomala et al., 2014), maximal active cervical spine flexion (Cruz-Montecinos et al., 2016) and active pelvic anteversion "over a distance" (Cruz-Montecinos et al., 2015).

3.2.4. Measurement sites and procedures used to standardize the US probe location

The studied fasciae were assessed at different sites, and the US transducer location was retained either manually or using a fixing device.

In the femoral region, the US transducers were positioned halfway between the greater trochanter and the lateral epicondyle of the femur for VL deep fascia (Ichikawa et al., 2015) and ileo-tibial

Table 3
Methodological US imaging of the crural deep fascial sliding.

US MACHINE	IMAGING MODE	TRANSDUCER					SUBJECTS POSITION	OUTCOME MEASURE(S)	RELIABILITY	PROCEDURES USED TO INDUCE FASCIAL SLIDING	FASCIAL SLIDING ANALYSIS METHOD
		Array type	Freq. (MHz)	Depth (cm)	Location	Handling					
Luomala et al. (2014) GE Healthcare's LOGIQ P6	B-mode	Linear	9–15	NS	(1) gastrocnemius lateral part, halfway up the calf, towards the peroneus muscle (2) medial to the biceps femoris, midway on thigh	Manual	Prone-lying	Fascial gliding	NA	Fascial Manipulation® + active, maximal dorsi & plantar flexion	Start and end frames comparison
Cruz-Montecinos et al. (2015) SonoSite TITAN®; Sonosite, Bothell, WA, USA	B-mode	Linear	5–10	3.9	On the muscle belly of the medial gastrocnemius on the dominant limb	Fixing device	Siting	Fascial displacement	Intra-rater: ICC = 0.903 Manual tracking VS LKP tracking: - ICC = 0.973 - average difference between methods < 0.95%	Active pelvic anteversion (start at maximum retroversion)	Cross-correlation software techniques (automatic tracking)
Cruz-Montecinos et al. (2016) SonoSite TITAN®; Sonosite, Bothell, WA, USA	B-mode	Linear	5–10	3.9	On the muscle belly of the medial gastrocnemius on the dominant limb	Fixing device	Siting	Fascial displacement	NA	Maximal active cervical spine flexion (start at neutral position)	Cross-correlation software techniques (automatic tracking)

Legend – US: ultrasound; ICC: Intraclass correlation coefficient; Freq.; frequencies; NS: not stated; NA: not available.

band (fascia lata) assessment (Condino et al., 2015); and "18 cm superior to the middle of the superior edge of the patella" (Langevin et al., 2007) or "between rectus femoris and VL muscles, 15 cm rostral to the patella and over the belly of the rectus femoris" (Fox et al., 2014) for evaluation of the anterior thigh perimuscular fascia. The probe positions were standardized by a fixing device (Condino et al., 2015; Fox et al., 2014) or by placing aluminum tape on the patient's skin, which "appears as a reference black vertical shadowed band on the US image to stabilize the position and orientation of the probe" (Ichikawa et al., 2015).

Deep fascia in the crural area was analyzed using the transducers positioned over the lateral (Luomala et al., 2014), and medial (Cruz-Montecinos et al, 2015, 2016) bellies of the gastrocnemius muscle and the positions were standardized by a black-marked spot on the skin (Luomala et al., 2014) or using a fixing device (Cruz-Montecinos et al, 2015, 2016).

3.2.5. *Outcome measures and fascial sliding analysis methods*

A multiplicity of terms was used to describe the outcome measures which conveyed the sliding between fascial layers, namely: "displacement" (Langevin et al., 2007), "axial and lateral tissue displacement" and "shear strain between layers" (Fox et al., 2014), "fascial gliding motion" (Ichikawa et al., 2015) and "fascial layers mobility" (Condino et al., 2015) for the femoral region fasciae; and "fascial gliding" of the superficial, middle and deepest sublayers of the deep fascia (Luomala et al., 2014) and "deep fascia displacement" (Cruz-Montecinos et al, 2015, 2016) for the crural region fasciae.

All the studies recorded US videos to analyzed and quantified fascial mobility. The same videos were later analyzed using different strategies. Cross-correlation software techniques using automatic tracking algorithms were employed to measure femoral (Condino et al., 2015; Fox et al., 2014; Langevin et al., 2007), and crural (Cruz-Montecinos et al, 2015, 2016) regions fasciae sliding motion. Additionally, start (usually in a relaxed muscular state) and end (usually in a target muscular contraction state) US frames comparisons were also used to measure the sliding motion of femoral (Ichikawa et al., 2015) and crural region fasciae (Luomala et al., 2014).

3.2.6. *Reliability of fascial sliding measurements*

The intra-rater reliability of the US measurements for the femoral fasciae mobility was accessed by Ichikawa et al. (2015), who aimed to compare the effects of myofascial release and hot pack therapy on fascial gliding of the deep fascia of the VL muscle by measuring tissue changes using US. The authors found high reliability of the US measurement, which used an external marker as a reference point (Ichikawa et al., 2015). The work developed by Condino et al. (2015) proposed the application of "3D US screening for the *in vivo* 3D fascial motion assessment" and presented an innovative semiautomatic method allowing, for each fascial layer, "the estimation and the validation of a 3D motion vector field describing the displacement of salient fascial features during a muscular contraction"; the validation process to evaluate the reliability of salient fascial feature matches consisted of inter-rater agreement among three experienced radiologists, and the authors concluded that the results "preliminarily demonstrate the viability of the proposed method for estimating the 3D fascial motion from 3D US datasets" (Condino et al., 2015).

Only one article assessed the intra-rater reliability of the US measurements in the crural region. Cruz-Montecinos et al. (2015) found very high reliability between manual tracking and tracking with the Lucas–Kanade pyramidal algorithm (ICC = 0.973) and good intra-rater reliability for the model of myofascial connectivity over a distance between the pelvis and leg (ICC = 0.903) (Cruz-Montecinos et al., 2015).

4. Discussion

4.1. Study designs and levels of evidence

The present review highlights the cross-sectional as the study design elected to explore deep fascia sliding *in vivo*, especially for diagnosis purposes. Most of the articles explored diagnosis questions, which is plausible given the novelty of the matter and the need to develop valid and reliable diagnostic tools for later application in experimental clinical settings.

A lack of RCTs on the theme is revealed.

4.2. Sample characteristics

In general, the study samples included in this review were small [particularly those assessing the femoral and crural regions fasciae ($n \leq 17$)] and included more men than women. Langevin et al. (2011) suggested that there “appears to be some sex-related differences in TLF shear strain that may also play a role in altered connective tissue function” (Langevin et al., 2011). Thus, special attention should be given to possible sex-related influences, such as hormonal differences, in fascial layers sliding.

Studied samples also included mostly healthy young individuals. Concerning this limitation, Cruz-Montecinos et al. (2015) questioned the replicability of their results, as the studies focused only on young men with a healthy weight since, under other conditions, the US soft tissue artifacts could generate a greater range of error (Cruz-Montecinos et al., 2015). In fact, a body mass index within the recommended parameters was one of the inclusion criteria in several studies (Chen et al, 2014, 2015; Cruz-Montecinos et al., 2015; Griefahn et al., 2017; Tu et al., 2016). So, it is relevant to understand if different body compositions, clinical conditions, or ages influence fascial mobility and if the US methods present the same levels of reliability and diagnostic accuracy.

4.3. US equipment characteristics

The authors of the included studies used a multiplicity of US devices and different types of transducers. Femoral (Fox et al., 2014; Ichikawa et al., 2015; Langevin et al., 2007), and crural region fasciae (Cruz-Montecinos et al, 2015, 2016; Luomala et al., 2014) were visualized through linear array transducers, “the workhorse transducer for musculoskeletal imaging” (Adams, 2013).

Regarding the frequency and depth of acquisition, emphasis should be given to the fact that specific data were rarely available. Only one study reported the depth of 4 cm to assess the thigh fascia (Langevin et al., 2007), while two studies revealed 3.9 cm of depth for the crural fascia imaging (Cruz-Montecinos et al, 2015, 2016). Specific information would be beneficial to allow comparisons and to standardize the US evaluation methods for different anatomical structures, namely deep fasciae.

The frequency ranges of the US probes used in the included articles varied from 4 MHz to 15 MHz. High-frequency probes seem to provide high-quality images at a low depth, whereas low-frequency probes are best at giving more in-depth structure images, though image clarity (Adams, 2013) may be compromised. Adams (2013) explains that “the vast majority of musculoskeletal US work is carried out at 10 MHz, with a smattering at 12 MHz for the more superficial structures (within 2 cm depth) and some at 8 MHz for slightly deeper structures (4–5 cm depth)” (Adams, 2013). Bogaerts et al. (2017) used a high-frequency (21 MHz) US acquisition system to explore the intratendinous deformation patterns of normal Achilles tendons *in vivo* using US-based speckle tracking (Bogaerts et al., 2017). Similarly, fascial mobility research may consider the use of high-frequency transducers, allowing the tracking of speckle patterns of smaller structures and henceforth a better description of tissue deformation.

Overall, conventional B-mode was the main US imaging mode used to assess fascial sliding mobility (Cruz-Montecinos et al., 2016, 2015; Ichikawa et al., 2015 . B-mode is the standard mode of US devices and produces a bi-dimensional grayscale cross-sectional image representing tissue and organ boundaries within the body (Peter Hoskins; Kevin Martin; Abigail Thrush, 2010). However, this US mode does not reproduce the 3D characteristic of fascial structures. It is worth mentioning the development of a 3D US evaluation model by Condino et al. (2015), specifically for the assessment of fascial mobility (Condino et al., 2015; Turini et al., 2015).

Elastography is a computational technique utilizing cross-correlation methods to quantify tissue motion based on a series of US images acquired in rapid succession (Langevin et al., 2011). This method was used in two studies to measure fascial lateral motion, allowing an estimation of femoral fascia sliding (Fox et al., 2014; Langevin et al., 2007).

4.4. Subjects positioning and procedures to induce fascial sliding mobility

In the studies' protocols composing this review, the positioning of the subjects depended on the procedure used to induce the fascial layers’ mobility. It must be stressed that only two studies assessed fascial force transmission over a distance through active movements (Cruz-Montecinos et al, 2015, 2016). On this matter, two systematic reviews focused on identifying scientific evidence on the transmission of tensile force along myofascial chains based on dissection and *in vivo* studies (Krause et al., 2016; Wilke et al., 2016). The authors suggested that future research should focus on the *in vivo* function of myofascial continuity during the application of actively or passively isolated tissue tension, including in exercise, prevention, and rehabilitation scenarios (Krause et al., 2016; Wilke et al., 2016).

4.5. Measurement sites and procedures used to standardize the US probe location

In all the studies, the US measurements of fascial sliding mobility were performed in a single place. This is a limitation underlined by some authors (Condino et al., 2015; Cruz-Montecinos et al., 2015; Ichikawa et al., 2015), along with the limited size of the US probe (Ichikawa et al., 2015).

Different possibilities exist that could be used in fascial sliding research to evaluate the fascial behavior in more than one place, including over a distance. Cruz-Montecinos et al. (2015) suggest the possibility of incorporating more than one transducer, allowing for simultaneously determining the fascia displacement over a distance (Cruz-Montecinos et al., 2015). In this regard, it is also worth mentioning Kellis et al. (2013) and Kellis (2016), who used two synchronized US probes to image the movement of hamstrings tendons (Kellis, 2016; Kellis et al., 2013). In turn, Raiteri et al. (2016) studied the tibialis anterior central aponeurosis width and length through a 3D-US method in which transverse sweeping scans were performed while video capture of the probe position was monitored and synchronized with the US images (Raiteri et al., 2016). However, such strategies may be methodologically more demanding and less viable in clinical practice.

Probe handling is essential to the proper performance of an accurate and repeatable US exam (Adams, 2013). Diagnostic accuracy of US measurements depends on the operator's technical capabilities (Erkonen, W. E., & Smith, 2009; Soni, N., Arntfield, R., & Kory, 2015), since it manually controls the transducer, so that variations in the compression pressure, orientation or direction of the probe can modify the resulting images (operator bias) (Drakonaki et al., 2009). The undesirable movement of the transducer and its impact on the slide measurements is a crucial concern reported by some authors (Crommert et al., 2017; Engell et al., 2016; Hides et al., 2007), given that the measurements aim to identify changes in the anatomic location over time, based on a sonogram that was kept in the same position (Crommert et al., 2017). To overcome this potential source of bias, there have always been efforts to standardize the US probe position at the site chosen for measurement. The fixation procedure used by some authors consisted of a custom probe fixing device (Condino et al., 2015; Cruz-Montecinos et al, 2015, 2016). When the US probe was manipulated external markers were used as reference points for the measurements made on the recorded US images (Ichikawa et al., 2015; Luomala et al., 2014).

4.6. *Outcome measures and fascial sliding analysis methods*

Several terminologies were used to describe the fascial sliding outcome measures. However, in order to facilitate the comparison between studies, uniformity of terminology related to fascia is necessary. In this review, the term "sliding" was used to summarize all the terms referring to the mobility between fascial collagen layers among themselves and concerning the underlying muscles and organs (Chaitow, 2017; Cowman et al., 2015; Roman et al., 2013; Stecco, 2015).

The technological evolution of the US equipment and the software with which the analysis and measurements are made has allowed greater diagnostic and methodological rigor over the years. Through the analysis of the works included in this review, an effective measurement of fascial sliding mobility through US using two main techniques was observed. The first consists of superimposing and comparing the initial and final positions of anatomical structures and/or their relation with external references ("start and end frames comparison") – used in 2 papers (Ichikawa et al., 2015; Luomala et al., 2014). The second refers to cross-correlation analysis techniques using automatic tracking software algorithms that compare the movement of greyscale, speckle features between individual US frames within specified regions of interest (also known as speckle tracking) ("cross-correlation software techniques") – used in 5 papers (Condino et al., 2015; Cruz-Montecinos et al, 2015, 2016; Fox et al., 2014; Langevin et al., 2007). Among the cross-correlation techniques, emphasis should be given to a semi-automatic method, based on the generation of a motion vector field describing, for each fascial layer, the displacement of salient fascial features during a muscular contraction, enabling a 3D US evaluation of fascia mobility *in vivo* (Condino et al., 2015).

4.7. *Reliability of fascial sliding measurements*

The studies in this review revealed that both US methods ("start and end frames comparison" and "cross-correlation software techniques") are reliable tools to measure fascial sliding *in vivo* at specific anatomic locations, which is consistent with the reliability found for the use of US to evaluate the peripheral nerve excursion (Kasehagen et al., 2018).

Cross-correlation software techniques showed to be highly reliable to measure the sliding between the crural fascia and the gastrocnemius epimysial fascia over the medial gastrocnemius muscle belly (Cruz-Montecinos et al., 2015). Cruz-Montecinos et al. (2015) found very high reliability between manual tracking and automatic tracking (Lucas–Kanade pyramidal algorithm) (Cruz-Montecinos et al., 2015).

Both "cross-correlation software techniques" and "superimposing and comparing start and end US frames" methods were considered reliable to assess the fascia lata sliding midway between the greater trochanter and lateral epicondyle of the femur (Condino et al., 2015; Ichikawa et al., 2015). Ichikawa et al. (2015) found high reliability of the comparison method, which used an external marker as a reference point for measurement (Ichikawa et al., 2015). On the other hand, the validation process to evaluate the reliability of salient fascial feature matches in the 3D US screening for the *in vivo* 3D fascial motion assessment model developed by Condino et al. (2015) consisted of inter-rater agreement among three experienced radiologists, and the authors concluded that the results "preliminarily demonstrate the viability of the proposed method for estimating the 3D fascial motion from 3D US datasets" (Condino et al., 2015).

Despite such favorable results, extrapolation of the reliability of the US methods to other fasciae should be carried out with caution.

4.8. *Limitations*

Despite the efforts to objectively limit the boundaries of this review to deep fasciae, their sliding mobility and respective *in vivo* US evaluation methods, the heterogeneity of the terminology used by the different authors to describe the fascial structures and their sliding mobility may have influenced the selection and analysis of the articles. Fascia has generated a passionate debate between clinical specialists and researchers, which has justified the creation of "The Fascia Nomenclature Committee" to reach consensus on related terminology (Adstrum et al., 2017; Stecco et al., 2018).

Although the scope of this review was limited to deep fascial sliding, other structures of the fascial system (such as aponeuroses, tendons or visceral fasciae) and fascial properties (such as its thickness, stiffness or state of hydration) must be highlighted due to their importance. Such structures, together with the sliding capacity, are involved in the normal functioning of the fascial system and, therefore, in efficient movement (Stecco, 2015; Zügel et al., 2018).

4.9. *Clinical relevance and research considerations*

1) US "start and end frames comparison" and "cross-correlation software techniques" are reliable tools to measure sliding *in vivo* of the femoral, and crural fasciae. Among these techniques, there is a US semiautomatic method that enables the 3D evaluation of fascia mobility *in vivo* during a muscular contraction. The use of these methods to analyze thorax, upper back, and upper limb fasciae sliding is not well established due to the lack of studies.
2) Linear array transducers appear to be the standard choice to assess femoral and crural fascial sliding.
3) The frequency and depth of image acquisition must be adjusted according to the studied fasciae and body composition. Standardization is still necessary.
4) B-mode is the standard US imaging mode to assess fascial sliding. The use of available 3D B-mode US methods should be emphasized as they reproduce the 3D characteristic of fascial structures.
5) Subjects positioning depends on the test procedures, which may include active and passive movements, passive maneuvers, or therapeutic techniques.
6) Measurement sites must be selected according to the studied fascia. A fixing device may be used to standardize the probe location. However, this is not usually suitable in clinical practice where the US assessments may be performed handling the probe and using reference marks to standardize the location.
7) The influence of sex and age in deep fascial sliding should be clarified.

5. Conclusions

US sliding measurements have used methods of superimposing and comparing start and end frames of an US video recording, and cross-correlation analysis through automated tracking algorithms, including a specific 3D B-mode model, developed to assess fascial mobility. These methods had proven to be reliable tools to measure sliding between the fascia lata, crural fascia, and the adjacent epimysial fasciae. However, the papers included in this review presented heterogeneous terminologies, research questions, participant populations, and methodologies. Thus, attention must be paid when extrapolating the reliability of those methods to other anatomical regions or populations. Therefore, high-quality research is necessary to determine the reliability of the current methods to assess other fasciae. Moreover, the influence of aging, sex-related characteristics, body composition, or specific clinical conditions on fascial sliding measurements needs further analysis. Terminological and methodological standardization is mandatory, and specific protocols are needed to assess each anatomical region so that the US assessment of fascial sliding *in vivo* can be adequately used in research and clinical practice, namely in movement therapy scenarios.

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