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Diagnostic Methods

Diagnostic ultrasound assessment of deep fascia sliding mobility *in vivo*: A scoping review – Part 1: Thoracolumbar and abdominal fasciae

Hélio Rafael Soares [a, *], Ana Rita Pinheiro [d], Carlos Crasto [b, c], Pedro Barbosa [b, c], Nuno Dias [a, c], Paulo de Carvalho [b, c]

[a] Escola Superior de Saúde Do Instituto Politécnico Do Porto (ESS-P. Porto), Porto, Portugal
[b] Centro de Estudos Do Movimento e Atividade Humana (CEMAH), Centro de Investigação Em Reabilitação (CIR), ESS-P.Porto, Porto, Portugal
[c] Área Técnico-Científica da Fisioterapia da ESS-P.Porto, Porto, Portugal
[d] Instituto de Biomedicina (iBiMED), Escola Superior de Saude, Universidade de Aveiro, Portugal

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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.

* Corresponding author.
E-mail address: rafael.soares.ost@gmail.com (H.R. Soares).

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1. Introduction

For many years, the scientific community has paid little attention to fascia. This is possibly due to the ubiquitous and apparently disordered nature of this tissue, or, most probably, because of the lack of adequate tools that can be used for its assessment (Klinger, W., & Schleip, 2015; Stecco et al., 2011). The recent evolution of histology and ultrasound (US) imaging evaluation led to a considerable increase in fascia-related research (Chaitow, L., & Schleip, 2012), especially regarding the role of this tissue in muscular force transmission (Krause et al., 2016; Wilke et al., 2016), movement perception and coordination (Schleip et al., 2012; Stecco et al., 2011; Turrina et al., 2013), and etiology of pain (Wells et al., 2013). In fact, reduced sliding movements between adjacent fascial layers may be associated with hyper-activation of free nerve endings, resulting in local inflammation, pain, sensitization, and potential movement dysfunction (Chaitow, 2014a, 2014b; Stecco, 2015).

The sliding mobility of fascial tissues has been assessed through manual palpation and US (Zügel et al., 2018). Although manual palpation represents a cost-neutral and widely used screening method aimed at assessing the viscoelastic properties of fascial tissues, its reliability is limited. In contrast, imaging methods such as tomography (CT), magnetic resonance imaging (MRI) and US are pointed out as reliable promising tools for explicitly quantifying the mechanical properties of fascial tissues *in vivo* (Zügel et al., 2018; Stecco, 2015). Although MRI and CT can provide a more objective view of the location and alterations of the fascial layers, US is less costly and allows measuring the thickness of the various sublayers and analysing the sliding between fascia and muscle and between the various fascial sublayers (Stecco, 2015). However, the use of diagnostic US procedures to assess fascial mobility and to monitor therapeutic interventions seems to be at a very embryonic stage (Roll, S. C., Asai, C., & Tsai, 2016). For researchers and clinical practitioners to be confident in US as an objective method for assessing fascia sliding, it is necessary to know what are the methods available and confirm that they have adequate levels of evidence.

Within this context, a scoping review was carried out aiming to identify, synthesize and collate the key methodological principles that have been described in the literature for US evaluation of 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.

In Part 1 of this two-part review we concentrate on the evidence obtained for the thoracolumbar and abdominal fasciae. The second part of this review will include evidence for the femoral and crural fasciae.

2. Methods

2.1. Information sources and search strategy

A systematic literature search was conducted according to the PRISMA-ScR guidelines (Tricco et al., 2018). The systematic search of health and science bibliographic databases was performed to identify potentially relevant articles for inclusion in this study. The databases consulted were ScienceDirect, PubMed (Medline), Web of Science, and B-On. No restriction was imposed on the publication date of the articles. The search was carried out between December 2017 and April 2018, using a consistent search strategy across all databases (Table 1) and including keywords from three main concepts: ultrasound imaging (ultrasound, ultrasonography, sonography), fascia (fascia, fascial, myofascial, neuromyofascial, connective) and sliding (slide, sliding, glide, gliding, motion, movement, mobility, mobilization, excursion, displacement). The Boolean operators “AND” and “OR” were used to link the keywords from each concept and to link the concepts themselves, respectively. After the selection of the articles, the list of references obtained was manually checked to identify any other potentially eligible article.

2.2. Eligibility criteria

The review included quantitative studies that used US imaging to assess sliding of deep fascia (muscular fascia according to the terminology of the Functional Atlas of the Human Fascial System (Stecco, 2015)) in humans, *in vivo*. Only articles with an available full-text version published in peer-reviewed journals were included in this review. Studies were excluded if they were: descriptive commentaries, conference abstracts or proceedings, review articles, pre-clinical and preliminary reports, or unavailable in English, Portuguese, or Spanish. Study characteristics for eligibility are detailed in Table 2.

2.3. Selection of sources of evidence

One reviewer screened all titles and abstracts of the articles identified in the literature search to assess potential eligibility. During the initial screening process an analysis of all articles titles and/or the abstract was carried out to decide and exclude ineligible articles. The full-texts of the remaining potentially eligible studies were obtained from the respective databases. Two reviewers independently appraised all identified studies against the inclusion and exclusion criteria to determine final eligibility. Differences in judgments were discussed with a third reviewer who acted as a referee to decide the final determination of eligibility.

2.4. Data charting process, data items and synthesis of results

A standardized data-charting form, based on the review objectives, was developed in Excel^{tm}. One reviewer extracted the relevant information from each eligible article, discussed the results with the team members, and continuously updated the data-charting form in an iterative process.

A global overview of the selected studies is presented in Table 3, including general data such as identification, demographic characteristics, level of evidence (LoE) (OCEBM Levels of Evidence Working Group et al., 2011b), study type assessment (using the “decision algorithm to help define study designs” (Peinemann and Kleijnen, 2015)), body region, and studied fascia.

Considering that the included studies addressed several body regions' fasciae, which might present regional specificities, a consensus among the review team members was reached to organize the included articles into four major groups: thoracolumbar, abdominal, femoral and crural. The review team members also agreed to include the transversus abdominis (TrA) muscle fascia in the group of fasciae of the abdominal region, although it constitutes an anatomical continuity with the anterior layer of the thoracolumbar fascia (TLF) (Stecco, 2015). 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

Table 1
Strategy for electronic database searches.

DATABASE	SEARCH FIELDS	SEARCH TERMS (database subject headings)
Sciencedirect PubMed (Medline) Web of Science B-on	Title, abstract, key words	(ultrasound OR ultrasonography OR sonography) AND (fascia OR fascial OR myofascial OR neuromyofascial OR connective) AND (slide OR sliding OR glide OR gliding OR motion OR movement OR mobility OR mobilization OR excursion OR displacement)

Table 2
Study characteristics for review eligibility (PICOS).

CHARACTERISTICS	INCLUSION	EXCLUSION
Participants	The study sample included human participants *in vivo* only.	Studies conducted in cadavers, animals or other models.
Intervention	US imaging was used to assess *in vivo* deep fasciae sliding.	
Control/ comparator	Not applicable. No control or comparators.	
Outcome measures	Studies in which one of the outcome measures was the US measurement of deep fascia layers' sliding (using either the term "sliding" or another term with a similar meaning).	
Study design	Quantitative study designs including randomized controlled trials (RCTs), pseudo-randomized controlled trials, cohort, cross-sectional, case series, case control, or case studies.	Descriptive commentaries, conference abstracts or proceedings, review articles, pre-clinical and preliminary reports.
Publication	Peer-reviewed publications. Full text available.	Articles not available in English, Portuguese or Spanish.

description of reliability analysis for the employed US measurements, the procedures used to induce fascial sliding, and the methods used for fascial sliding analysis.

2.5. Critical appraisal of individual sources of evidence

One reviewer used the OCEBM LoE to assess each article. The OCEBM LoE is an easy and effective tool to evaluate the strength of results in research studies (OCEBM Levels of Evidence Working Group et al., 2011a). This classification rapidly estimates the methodological quality of each article (Howick et al., 2011). According to this system, articles were classified from level I (higher LoE) to V (lower LoE), where higher LoE means better methodological quality and lower risk of bias (Howick et al., 2011).

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 3 shows the general characteristics of the articles included in the current review; Tables 4 and 5 group the methodological data from the studies of the thoracolumbar (n = 4), abdominal (n = 7) regions.

3.2.1. Study designs and levels of evidence

According to their methodological design, most of the papers included in the review were observational cross-sectional studies (72.1%; n = 13) (Chen et al, 2014, 2015; Condino et al., 2015; Crommert et al., 2017; Cruz-Montecinos et al, 2015, 2016; Fox et al., 2014; Hides et al., 2007b; Jhu et al., 2010; Langevin et al., 2007, 2011; Murakami et al., 2011; Tu et al., 2016). The remaining studies were within-group comparison studies (also known as before-and-after studies) (n = 2) (Engell et al., 2016; Hides et al., 2007b), one prospective cohort study (Ichikawa et al., 2015), one case study (Luomala et al., 2014), and one RCT that assessed the thoracolumbar region (Griefahn et al., 2017).

This systematic research reports papers with levels of evidence ranging from II to IV: LoE II (61.1%; n = 11), LoE III (33.3%; n = 6), LoE IV (5.6%; n = 1). Most of the articles (61.1%; n = 11) focused on diagnosis questions, while the remaining studies (38.9%; n = 7) analyzed treatment benefits. There was a tendency for articles analyzing diagnostic questions to present slightly higher levels of evidence [LoE II (n = 10) and III (n = 1)] than those that addressed treatment benefits [LoE II (n = 1), III (n = 6) and IV (n = 1)]. All body regions presented articles rated as LoE II and III, except for the crural region that presented two studies with LoE II and another with LoE IV.

3.2.2. Sample characteristics

From the 18 included articles, only four presented sample sizes with more than 30 participants (Chen et al., 2014; Griefahn et al., 2017; Langevin et al., 2011; Murakami et al., 2011); sample sizes in individual studies ranged from 1 (Luomala et al., 2014) to 121 participants (Langevin et al., 2011). Overall, the 18 articles included in the current review involved 450 participants.

Altogether, the studies of the thoracolumbar and abdominal regions involved more participants (195 and 185, respectively) than those addressing the femoral and crural regions (37 and 33, respectively). Globally, 63.1% of the participants were men (n = 284), and 36.9% were women (n = 166), although the studies assessing the crural region fasciae included only men. Most of the participants (68.7%; n = 309) were asymptomatic, and the remaining 31.3% (n = 141) presented some clinical condition. In the three crural region studies, only the case-study presented a subject

Table 3
General characteristics of included studies.

BODY REGION	STUDY IDENTIFICATION	STUDIED FASCIAE	SAMPLE CHARACTERISTICS						STUDY TYPE (Peinemann and Kleijnen 2015)	OCEBM LEVEL OF EVIDENCE	
			Sample Size	n males	n females	n healthy	n clinical condition	Mean age (years)		Question	Level
Thoraco-lumbar (n = 4)	Langevin et al. (2011)	Thoracolumbar fascia (posterior layer)	121	62	59	50	71	43.2	Cross-sectional	Diagnosis	II
	Tu et al. (2016)	Thoracolumbar fascia (posterior layer)	12	8	4	12	0	22.9	Cross-sectional	Treatment	III
	Griefahn et al. (2017)	Thoracolumbar fascia (posterior layer)	38	13	25	38	0	23.3	Randomized controlled trial	Treatment	II
	Engell et al. (2016)	Thoracolumbar fascia (posterior layer) + Epimysial fascia of the thoracic paraspinal tissues	24	24	0	24	0	25.0	Within-group comparison	Treatment	III
		TOTAL	**195**	**107**	**88**	**124**	**71**	**28.6**			
Abdominal (n = 7)	Hides, Wong, et al. (2007)	TrA anterior muscle-fascia junction	19	8	11	19	0	20.3	Cross-sectional	Diagnosis	II
	Hides, Miokovic, et al. (2007)	TrA anterior muscle-fascia junction	19	8	11	19	0	20.3	Within-group comparison	Diagnosis	III
	Jhu et al. (2010)	TrA anterior muscle-fascia junction	18	14	4	18	0	22.6	Cross-sectional	Diagnosis	II
	Murakami et al. (2011)	TrA anterior and posterior muscle-fascia junctions	51	51	0	14	37	22.9	Cross-sectional	Diagnosis	II
	Chen et al. (2014)	TrA anterior and posterior muscle-fascia junctions	40	25	15	20	20	25.4	Cross-sectional	Treatment	III
	(Chen et al., 2015a)	TrA anterior and posterior muscle-fascia junctions	20	12	8	20	0	25.4	Cross-sectional	Diagnosis	II
	Crommert et al. (2017)	TrA anterior muscle-fascia junction	18	5	13	18	0	22.0	Cross-sectional	Diagnosis	II
		TOTAL	**185**	**123**	**62**	**128**	**57**	**22.7**			
Femoral (n = 4)	Langevin et al. (2007)	NS (fascia lata; quadriceps epimysial fascia)	12	1	11	0	12	24–74	Cross-sectional	Diagnosis	II
	Fox et al. (2014)	Fascia lata; Quadriceps epimysial fascia	11	6	5	11	0	21–57	Cross-sectional	Treatment	III
	Ichikawa et al. (2015)	Deep fascia of the vastus lateralis (fascia lata; vastus lateralis epimysial fascia)	12	12	0	12	0	27.0	Cohort	Treatment	III
	(Condino et al., 2015a)	Iliotibial band (fascia lata)	2	2	0	2	0	31.5	Cross-sectional	Diagnosis	II
		TOTAL	**37**	**21**	**16**	**25**	**12**	**29.3**			
Crural (n = 3)	Luomala et al. (2014)	Crural fascia (deep fascia in the calf area)	1	1	0	0	1	40.0	Case report	Treatment	IV
	Cruz-Montecinos et al. (2015)	Deep fascia of the medial gastrocnemius (epimysial fascia)	17	17	0	17	0	22.8	Cross-sectional	Diagnosis	II
	Cruz-Montecinos et al. (2016)	Deep fascia of the medial gastrocnemius (epimysial fascia)	15	15	0	15	0	23.0	Cross-sectional	Diagnosis	II
		TOTAL	**33**	**33**	**0**	**32**	**1**	**28.6**			
		TOTAL	**450**	**284**	**166**	**309**	**141**	**26.1**			
		TOTAL (%)	**%**	**63.1**	**36.9**	**68.7**	**31.3**				

Legend –TrA: transversus abdominis; OCEBM: Oxford Centre for Evidence-Based Medicine.

with a clinical condition. The participants were mainly young individuals with a mean age of 26.1 years; 2 studies of the femoral region only presented the minimum and maximum ages (Fox et al., 2014; Langevin et al., 2007).

3.2.3. Studied fasciae

The studies included in this review approached the mobility of several deep fascial layers. The articles related to the thoracolumbar region addressed the posterior layer of the TLF (Engell et al., 2016; Griefahn et al., 2017; Langevin et al., 2011; Tu et al., 2016) (the "superficial layer of the deep fascia of the back" (Stecco, 2015)) and one of them (Engell et al., 2016) also approached the superficial, intermediate and deep layers of the thoracic paraspinal tissues, which included the posterior layer of the TLF and the epimysial fascia of the of the erector spinae (which belongs to the "deep layer of the deep fascia of the back" (Stecco, 2015)).

The articles that assessed the fascial mobility of the abdominal region fasciae focused on the movement of the anterior and/or posterior muscle-fascia junctions of the TrA muscle (Chen et al, 2014, 2015; Crommert et al., 2017; Hides et al., 2007a, 2007b; Jhu et al., 2010; Murakami et al., 2011).

3.2.4. 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 thoracolumbar (Engell et al., 2016; Griefahn et al., 2017; Langevin et al., 2011; Tu et al., 2016) region was always assessed with linear array transducers, while both curvilinear (Hides et al., 2007a, 2007b) and linear (Chen et al, 2014, 2015; Crommert et al., 2017; Jhu et al., 2010; Murakami et al., 2011) array transducers were used to evaluate the abdominal region fasciae.

Most articles presented the US transducer frequency ranges, which overall varied from 4 MHz to 15 MHz. However, specific acquisition frequencies were rarely reported. One paper (Engell et al., 2016) revealed the acquisition frequency (10 MHz) used in the thoracolumbar region to assess the TLF, and another (Murakami

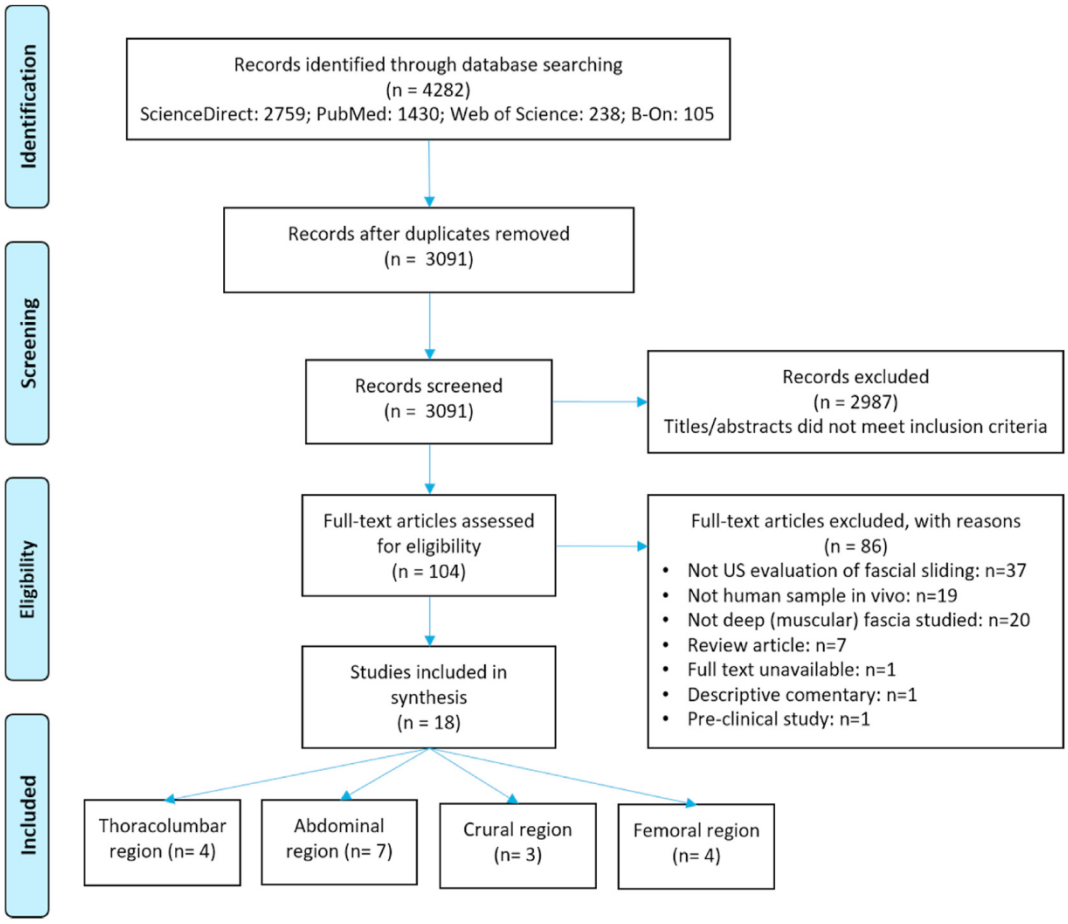

Fig. 1. PRISMA flow diagram of studies identified, screened, selected and included in the review.

Table 4
Methodological US imaging of the thoraco-lumbar 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. (2011)											
Terason 3000; Teratech Corporation, Burlington, MA	B-mode Elastography	Linear	10	4	2 cm lateral to the midline at the level of the L2-L3 interspace	Fixing device	Prone-lying	Shear strain	Intra-rater: ICC = 0.98	Passive trunk flexion (motorized articulated table)	Cross-correlation software techniques (automated tracking)
Tu et al. (2016)											
Voluson i; GE Healthcare; WI, USA	B-mode (3D)	Linear	4–12	NS	3 cm lateral to the middle of the L2-L3 spinous processes	Fixing device	Standing	Paracutaneous tissue translation	NA	Active velocity-guided lumbar flexion with and without KT	Cross-correlation software techniques (3D automated tracking)
Griefahn et al. (2017)											
MyLab One; Esaote Biomedica Germany	B-mode	Linear	6–13	NS	2 cm lateral to L2-L3 intervertebral space	Fixing device	Sitting	Fascial mobility	NA	Active thoracolumbar flexion of 30°	Cross-correlation software techniques (automated tracking)
Engell et al. (2016)											
Sonix RP, Burnaby, BC, Canada	B-mode; Elastography	Linear	10	4	≈ 2 cm left of the spine's T7 segment midline	Fixing device	Prone-lying	Cumulative caudocephalic displacement; Relative shear	NA	Passive preload manoeuvre	Cross-correlation software techniques (automated tracking)

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

et al., 2011) mentioned an acquisition frequency of 7.5 MHz to visualise the sliding of the TrA anterior muscle-fascia junction.

The US acquisition depth data were also scarce. A specific acquisition depth of 4 cm was reported in two studies of the

Table 5
Methodological US imaging of the abdominal 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					
Hides, Wong, et al. (2007)											
Synergy; GE Diasonics, San Jose, CA	B-mode	Curvilinear	5	NS	Perpendicular to the anterolateral abdominal muscles	Manual	Supine-lying	Slide of the anterior abdominal fascia	NA	Active static weight-bearing heel press (0% & 25% of body weight)	Start and end frames comparison
Hides, Miokovic, et al. (2007)											
Synergy; GE Diasonics, San Jose, CA	B-mode	Curvilinear	5	NS	Perpendicular to the anterolateral abdominal muscles	Manual	Supine hook-lying	Slide of the anterior abdominal fascia	Intra-rater: - across measurements from the same image: ICC = 0.98 - across images: ICC = 0.44 - across 2 days: ICC = 0.36	Abdominal drawing-in manoeuvre	Start and end frames comparison
Jhu et al. (2010)											
HDI 5000; Philips/ ATL, Bothell, WA, USA	B-mode	Linear	5–12	NS	At the level of the umbilicus, laterally transverse to the midline	Manual	Supine hook-lying	Changes in TrA length	Intra-rater: - ICC>0.75 - Within-subject CV <10%	Abdominal drawing-in manoeuvre	Start and end frames comparison
Murakami et al. (2011)											
NEMIO SSA-550A, Toshiba	B-mode	Linear	7.5	NS	At the level of the umbilicus (anterior, anterolateral and posterior sides)	Manual	Supine-lying	Distance of fascia motion	Intra-rater: - anterior: 0.90 < ICC<0.91 - anterolateral: 0.90 < ICC<0.92 - posterior: 0.88 < ICC<0.90	Abdominal drawing-in manoeuvre	Start and end frames comparison
Chen et al. (2014)											
HDI 5000; Philips/ ATL, Bothell, WA, USA	B-mode	Linear	5–12	NS	Inferior angle of the rib cage, at the level of the umbilicus (anterior or posterolateral sides)	Manual	Supine crook-lying	Sliding of the TrA muscle-fascia junction	NA	Abdominal drawing-in manoeuvre + myofascial release	Start and end frames comparison
(Chen et al., 2015a)											
Terason t3000; Teratech Corporation, Burlington, MA	B-mode	Linear	5–12	NS	Inferior angle of the rib cage, at the level of the umbilicus (posterolateral side)	Manual	Supine crook-lying	Sliding of the TrA muscle-fascia junction	Intra-rater: - ICC>0.70	Abdominal drawing-in manoeuvre	Start and end frames comparison
Crommert et al. (2017)											
Vivid 7; GE-Vingmed US Horten, Norway	B-mode	Linear	10	NS	Halfway between the 11th costal cartilage and the iliac crest	Manual	Standing	Fascial slide	NA	Flexed and extended shoulder static positions, 3 kg in each hand	Start and end frames comparison

Legend – US: ultrasound; ICC: Intraclass correlation coefficient; Freq.; frequencies; NS: not stated; NA: not available; CV: coefficient of variation; TrA: transversus abdominis (TrA).

thoracolumbar region fasciae (Engell et al., 2016; Langevin et al., 2011) Jhu et al. underline that the acquisition depth to assess the TrA anterior muscle-fascia junction was "automatically adjusted by the scanning depth" (Jhu et al., 2010).

The available data revealed that B-mode was the imaging mode employed in most of the studies (Chen et al, 2014, 2015; Crommert et al., 2017; Griefahn et al., 2017; Hides et al., 2007a, 2007b; Jhu et al., 2010; Murakami et al., 2011). 3D B-mode Tu et al. (2016) and B-mode with elastography (Engell et al., 2016; Langevin et al., 2011) were also used to explore fascial sliding of the thoracolumbarfasciae, while the abdominal region fasciae were explored with standard B-mode only.

3.2.5. Subjects positioning and procedures to induce fascial sliding mobility

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

In the thoracolumbar region, there was no pattern, and in some studies the participants were evaluated in prone-lying (Engell et al., 2016; Langevin et al., 2011), standing (Tu et al., 2016) and sitting (Griefahn et al., 2017) positions. Thoracolumbar flexion movements were used to induce fascial sliding either actively (Griefahn et al., 2017), passively using a motorized articulated table (Langevin et al., 2011), or by combining active lumbar flexion with Kinesiotape® (Tu et al., 2016). On the other hand, Engell et al. (2016) applied a passive maneuver to induce tension in the thoracic paraspinal tissue layers (Engell et al., 2016).

In most studies of the abdominal region, the individuals were assessed supine (Hides et al., 2007b; Murakami et al., 2011) or supine-crook/hook lying (Chen et al, 2014, 2015; Hides et al., 2007a; Jhu et al., 2010), but one study evaluated them standing (Crommert et al., 2017). The TrA activation, which is performed through an abdominal drawing-in maneuver, was the main procedure used to induce fascial sliding (Chen et al, 2014, 2015; Hides et al., 2007a; Jhu et al., 2010; Murakami et al., 2011). Chen et al. (2014) have also applied a passive myofascial release technique (Chen et al., 2014), and in the study by Crommert et al. (2017), the fascial slide was induced by "holding both arms symmetrically while standing, in flexed and extended shoulder static positions, with a dumbbell in each hand" (Crommert et al., 2017).

3.2.6. 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.

The TLF was assessed 2 or 3 cm laterally to the midline at the level of the L2-L3 intervertebral space (Griefahn et al., 2017; Langevin et al., 2011; Tu et al., 2016), and Engell et al. (2016) placed the transducer 2 cm laterally to the T7 segment midline to investigate the thoracic paraspinal tissues (Engell et al., 2016). Every study used a different procedure to standardize the US probe location by fixing one of its ends to the participants' skin with surgical tape (Langevin et al., 2011), with some type of template structure (Griefahn et al., 2017; Tu et al., 2016) or with a clamping system (Engell et al., 2016).

For the abdominal region imaging procedures, all the authors manually handled the transducers, and the level of the umbilicus was the main anatomical reference (Chen et al, 2014, 2015; Jhu et al., 2010; Murakami et al., 2011), except for Crommert et al. (2017), who used the 11th costal cartilage and the iliac crest (Crommert et al., 2017). However, to standardize the transducer position and to accomplish the fascial mobility measurements, different tactics were used. These included: 1) matching anatomic references (like the anterior and the posterior myofascial insertions of the TrA muscle) with the outer edges of the US image (Crommert et al., 2017; Hides et al., 2007a, 2007b; Jhu et al., 2010; Murakami et al., 2011); 2) using external markers on the participants skin (Murakami et al., 2011) such as "nylon threads, made of US echo-absorptive material, attached to the participant's abdomen with adhesive tape to generate a reference line on the US image" (Chen et al, 2014, 2015; Jhu et al., 2010); or 3) via a belt with a hole cut out that fitted the transducer, wore by the participants to help minimize the transducer movement (Crommert et al., 2017).

3.2.7. 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: "shear strain" (Langevin et al., 2011), "paracutaneous tissue translation" (Tu et al., 2016), (fascial) "mobility" (Griefahn et al., 2017) and "relative shear deformation" (Engell et al., 2016) for the thoracolumbar fasciae; and (fascial) "slide" or "sliding" (Chen et al, 2014, 2015; Crommert et al., 2017; Hides et al., 2007a, 2007b; Jhu et al., 2010) and "distance of fascia motion" (Murakami et al., 2011) for the abdominal 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 thoracolumbar (Engell et al., 2016; Griefahn et al., 2017; Langevin et al., 2011; Tu et al., 2016) fasciae sliding motion. On the other hand, start (usually in a relaxed muscular state) and end (usually in a target muscular contraction state) US frames comparisons were used to measure the sliding motion of abdominal (Chen et al, 2014, 2015; Crommert et al., 2017; Hides et al., 2007a, 2007b; Jhu et al., 2010; Murakami et al., 2011) region fasciae. Interestingly, all studies targeting the thoracolumbar region used only cross-correlation software techniques, and abdominal region studies used only start and end frames comparison.

3.2.8. Reliability of fascial sliding measurements

Eight of the eighteen studies in this review analyzed the reliability of the fascial sliding outcome measures. In one of the four thoracolumbar region papers, Langevin et al. (2011) concluded that the intra-rater reliability of US measurements of TLF shear strain calculations was high (ICC = 0.98) (Langevin et al., 2011). Four out of seven studies (Chen et al., 2015; Hides et al., 2007a; Jhu et al., 2010; Murakami et al., 2011) assessed the intra-rater reliability of the US fascial sliding measures used in the abdominal region and revealed overall good to excellent reliability. In particular, the reliability of measuring the slide of the anterior abdominal fascia by a novice physical therapist rater was studied, and the results yielded "very high reliability across measurements from the same image, but very low reliability across images and different days" (Hides et al., 2007a).

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 also revealed. The single RCT that was found analyzed the TLF sliding in a LoE II treatment benefits study. All other papers that focused on treatment benefits scored lower levels of evidence.

4.2. Sample characteristics

In general, the study samples included in this review were small 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. Studied fasciae

The abdominal (TrA fascia) and thoracolumbar fasciae (TLF and epimysial fasciae of the erector spinae) were the most studied. The interest in studying the properties of this region's fasciae may be justified by their role in lumbar segmental control and low back pain. The TLF is a significant aponeurotic fascia that plays an essential role in the transfer of loads between the trunk and the extremities and helps to maintain the stability of the lumbosacral area (Stecco, 2015). The remaining studies explored the lower limb fascia.

Emphasis should be given to the fact that no studies have been found that address the thorax, the upper back, and the upper limb fasciae. It is not clear that the conclusions about the measurement of fascial sliding *in vivo* drawn from the studies composing this review can be extrapolated to other regions. This limitation is in line with Condino et al. (2015), which considered that "other anatomical regions must be analyzed and specific protocols for the acquisition of 3D US musculoskeletal datasets in each anatomical region should be defined" (Condino et al., 2015). These authors also affirmed that further refinements in their 3D model are needed "to improve the effectiveness of the algorithm in specific anatomical regions" and that "the muscular contraction tasks must be standardized."

4.4. US equipment characteristics

The authors of the included studies used a multiplicity of US devices and different types of transducers. Thoracolumbar fasciae (Engell et al., 2016; Griefahn et al., 2017; Langevin et al., 2011; Tu et al., 2016) were visualized through linear array transducers, "the workhorse transducer for musculoskeletal imaging" (Adams, 2013). Both linear (Chen et al, 2014, 2015; Crommert et al., 2017; Jhu et al., 2010; Murakami et al., 2011) and curvilinear transducers (Hides et al., 2007a, 2007b) were used in the abdominal region assessments. Curvilinear arrays are the tools of choice for most general imaging applications involving the abdomen (Adams, 2013).

Regarding the frequency and depth of acquisition, emphasis should be given to the fact that specific data were rarely available. Only two studies reported the depth of 4 cm to assess the TLF (Engell et al., 2016; Langevin et al., 2011). 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 (Chen et al, 2014, 2015; Crommert et al., 2017; Griefahn et al., 2017; Hides et al, 2007a, 2007b; Jhu et al., 2010; Murakami et al., 2011). 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 et al., 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 some studies to measure fascial lateral motion, allowing an estimation of fascial sliding (Engell et al., 2016; Langevin et al., 2011).

4.5. 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. These procedures involved active and passive isolated movements, passive maneuvers, passive therapeutic techniques, and passive treatment techniques combined with passive and active movements. However, none of the studies for the thoracolumbar or abdominal fasciae assessed fascial force transmission over a distance through active movements. 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).

4.6. 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; Langevin et al., 2011; Murakami et al., 2011; Tu et al., 2016), along with the limited size of the US probe (Chen et al., 2014; Ichikawa et al., 2015; Langevin et al., 2011;

Murakami et al., 2011; Tu et al., 2016). For instance, Chen et al. (2014) explained that the changes that occurred at anterior and posterior sites of the muscle-fascial junction of the TrA could not be measured simultaneously by US due to the limitation of the transducer (Chen et al., 2014).

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, Raitieri 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., 2007a), 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). Engell et al. (2016) stressed that the problems with out-of-plane motion may interfere with the fascial movement software analysis method (speckle tracking) (Engell et al., 2016). In reference to such problem, Crommert et al. (2017) stated that "standardized placement of the US transducer and keeping it still during recordings are critical in sonography" (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. Several fixation procedures were used, such as fixing one of the probe's ends to the participants' skin with surgical tape (Langevin et al., 2011), building a template structure (Griefahn et al., 2017; Tu et al., 2016) or using a custom probe fixing device (Engell et al., 2016). When the US probe was manipulated, other strategies were used to standardize the measurement position, such as matching anatomic references with the outer edges of the US image (Crommert et al., 2017; Hides et al., 2007a, 2007b; Jhu et al., 2010; Murakami et al., 2011) or using external markers as reference points for the measurements made on the recorded US images (Chen et al, 2014, 2015; Jhu et al., 2010; Murakami et al., 2011).

4.7. 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 7 papers (Chen et al, 2014, 2015; Crommert et al., 2017; Hides et al., 2007a, 2007b; Jhu et al., 2010; Murakami et al., 2011). 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 4 papers (Engell et al., 2016; Griefahn et al., 2017; Langevin et al., 2011; Tu et al., 2016).

US techniques measuring mobility have been used in various body tissues. A systematic review carried out by Kasehagen et al. (2018) about peripheral nerve excursion found that speckle tracking (cross-correlation software technique) was the most commonly reported protocol for US imaging measurements of nerve excursion *in vivo*, having been used in 13 of the 18 studies, followed by digital measurement of the change in nerve position between the first and final frames of US video recordings and, finally, the use of real-time spectral Doppler US imaging to quantify nerve excursion (Kasehagen et al., 2018). Likewise, tendon excursion/displacement has also been extensively measured by speckle tracking cross-correlation techniques (An et al., 2010; Bogaerts et al., 2017; Chen et al., 2004; J.H. Korstanje et al., 2012; J.W.H. Korstanje et al., 2012; Van Doesburg et al., 2012; Yoshii et al., 2009) and Doppler US imaging (Kociolek and Keir, 2015; Oh et al., 2007; Sumi and Sato, 2008; Tat et al, 2013, 2015).

4.8. 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 of the TLF at the level of the L2-L3 interspace (Langevin et al., 2011).

Furthermore, superimposing and comparing start and end US frames was considered reliable to assess the sliding of the TrA at the anterior (Chen et al., 2015; Hides et al., 2007a; Jhu et al., 2010; Murakami et al., 2011) and posterior (Chen et al., 2015; Murakami et al., 2011) muscle-fascia junctions at the level of the umbilicus.

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

4.9. 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).

4.10. 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 TLFand TrA fasciae. 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 TLF sliding, whereas curvilinear transducers are used to study the abdominal fasciae.
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 TLF and TrA muscle-fascia junctions 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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