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Biomechanical properties of the human superficial fascia: Site-specific variability and anisotropy of abdominal and thoracic regions

Alice Berardo^{a,b}, Lorenza Bonaldi^{a,b,*}, Carla Stecco^{b,c}, Chiara Giulia Fontanella^{b,d}

^a Department of Civil, Environmental and Architectural Engineering, University of Padova, 35131, Padova, Italy

^b Centre for Mechanics of Biological Materials, University of Padova, 35131, Padova, Italy

^c Department of Neuroscience, Institute of Human Anatomy, University of Padova, 35121, Padova, Italy

^d Department of Industrial Engineering, University of Padova, 35131, Padova, Italy

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ABSTRACT

Superficial fascia is a fibrofatty tissue found throughout the body. Initially described in relation to hernias, it has only recently received attention from the scientific community due to new evidence on its role in force transmission and structural integrity of the body. Considering initial difficulties in its anatomical identification, to date, a characterization of the superficial fascia through mechanical tests is still lacking.

The mechanical properties of human superficial fasciae of abdominal and thoracic districts (back) of different subjects ($n = 4$) were then investigated, focusing on anisotropy and viscoelasticity. Experimental tests were performed on samples taken in two perpendicular directions according to body planes (cranio-caudal and latero-medial axes). Data collected from two different uniaxial tensile protocols, failure (i.e., ultimate tensile strength and strain at break, Young's modulus and toughness) and stress-relaxation (i.e., residual stress), were processed and then grouped for statistical analysis.

Failure tests confirmed tissue anisotropy, revealing the stiffer nature of the latero-medial direction compared to the cranio-caudal one, for both the districts (with a ratio of the respective Young's moduli close to 2). Furthermore, the thoracic region exhibited significantly greater strength and resultant Young's modulus compared to the abdomen (with greater results along the latero-medial direction, such as 6.13 ± 3.11 MPa versus 0.85 ± 0.39 MPa and 24.87 ± 15.23 MPa versus 3.19 ± 1.62 MPa, respectively). On the contrary, both regions displayed similar strain at break (varying between 38 and 47%), with no clear dependence from the loading directions. Stress-relaxation tests highlighted the viscous behavior of the superficial fascia, with no significant differences in the stress decay between directions and districts (35–38% of residual stress after 300 s).

All these collected results represent the starting point for a more in-depth knowledge of the mechanical characterization of the superficial fascia, which can have direct implications in the design, implementation, and effectiveness of site-specific treatments.

1. Introduction

In recent times, the scientific community has shown a growing interest in exploring the biomechanical properties of fascial connective tissues, due to their multiple clinical implications and engineering applications, such as reconstructive surgery and surgical patches by plastic surgeons (Jiang and Rinkevich, 2021; Sugo et al., 2020; Tiengo et al., 2013). When subjected to tension, the fascial tissue exhibits typical characteristics observed in other soft connective tissues (Bonaldi et al., 2023a; Singh and Chanda, 2021), being a fiber reinforced composite material. Fascia, originating from embryonic mesoderm, is a continuous

and viscoelastic connective tissue linking organs and tissues throughout the body (Iatridis et al., 2003; Stecco, 2014). It comprises various layers, such as superficial and deep fascia, retinacula, visceral fascia, aponeuroses, and sheaths. The functions of the fascial system include structural support, protection, force transmission, movement perception and coordination, cellular signal transmission with implications in neurological functions, and pain etiology (Adstrum et al., 2017; Benjamin, 2009). Muscle fascia includes aponeurotic fasciae and epimysial fasciae, which can be found fused in some regions of the body.

Among the fascial layers, superficial fascia from a histological perspective is composed of loose areolar connective tissue with

* Corresponding author. Department of Civil, Environmental and Architectural Engineering, University of Padova, 35131, Padova, Italy
E-mail address: lorenza.bonaldi@phd.unipd.it (L. Bonaldi).

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enveloped fat lobules (Stecco, 2014). The term ‘superficial fascia’ appeared only at the end of the nineteenth century with studies on the abdomen and pelvis. In 1825 Velpau affirmed that it is present throughout the body but unfortunately no one systematically continued its characterization, thus creating difficulties in its identification and nomenclature (Stecco, 2014). Nowadays, it has been proven that it plays a crucial role in maintaining structures integrity (i.e., vessel patency), supporting subcutaneous structures, and facilitating muscle and skin sliding. Extrinsic and intrinsic stimuli, such as manual therapies, temperature, and stretching practices could have a direct impact in superficial fascia sensitivity (such as nociception), e.g., physiotherapists commonly use mechanical stresses, as fascia manipulation for pain management and inflammation resolution (Stecco et al., 2023).

From a clinical perspective, it is crucial to understand the mechanical role and significance of the superficial fascia across various anatomical sites. The abdomen, frequently implicated in hernia repair surgeries, is a prime area of interest. Hernia repairs are among the most common surgical procedures worldwide, with over 20 million performed annually (Kingsnorth and LeBlanc, 2003). As the average age of the population rises, the frequency of surgeries for abdominal wall hernias is on the rise. Conversely, the superficial fascia of the thorax holds potential implications for back pain, a leading cause of disability worldwide (Buchbinder et al., 2020). The fascial system is believed to play a direct and significant role in back pain etiology and treatment (Langevin et al., 2009). Thus, understanding the mechanical characteristics of the superficial fascia in both the abdominal and thoracic regions is therefore essential for informing surgical interventions and therapeutic approaches targeting hernias and back pain, respectively.

However, few works focused on this connective tissue: in a work by Abu-Hijleh et al. (2006), they explored the presence of the superficial fascia in different body regions, analyzing its distribution, thickness and correlations with ultrasound imaging in-vivo. In term of thickness, in-vivo analysis was performed by Hammoudeh et al. through ultrasound, demonstrating that posterior chest had the highest average superficial fascia layer thickness of about 0.6 mm (Hammoudeh et al., 2022). More recently, in a study by Pandey et al. the superficial fascia from the abdomen was investigated, obtaining the elastic and collagen contents distribution (Pandey et al., 2016). Results highlighted that both percentages were significantly greater in the upper abdomen than that in the lower abdomen in males (collagen content of 13.5 % and elastic content of 14.6 % in the lower abdomen), while hydroxyproline content of superficial fascia of upper abdomen was significantly more than that of lower abdomen in both males and females. Pirri et al. evinced that the content of elastic fibers area in superficial fascia of the thigh is ten times higher than in the deep one (Pirri et al., 2022). Nevertheless, very little is known about the mechanical behavior of superficial fascia (Bonaldi et al., 2023b), as well as no standardized protocols for mechanical testing have been proposed for this specific tissue.

This being the case, in the present study, the main aim was to fit the gap regarding the mechanical properties of this tissue through an extended experimental campaign on samples harvested from two distinct anatomical regions such as abdomen and thorax from fresh-frozen human donors. Understanding the biomechanical properties of fascial tissue is crucial for various physiological functions and clinical applications.

2. Materials and methods

2.1. Sample harvesting and preparation

All procedures were conducted on human bodies from the “Donation to Science” Body Donation Program of the University of Padova and Veneto Region/National Reference Center for preserving and using gifted bodies (Registration number: IT-62435-16,764). Superficial fascia patches (2 from the abdomen and 2 from the back thorax) were harvested from a total of 4 subjects (85 ± 5 y/o, 3 males, 1 female) and

stored at -20 °C. The samples of superficial abdominal fascia were harvested below the arcuate line, while the superficial fascia of the back originated from the thorax in the right region superior to the rhomboid muscles. Anatomical landmarks were provided with the fascial patches, as reported in Fig. 1. The patches sizes were approximately $10 \text{ cm} \times 6 \text{ cm}$ each, depending on the availability of native tissue for each subject. They were thawed at room temperature and tested within 12 h, after being hydrated and cut into rectangular strips for mechanical testing.

Rectangular stripes were cut along the two orthogonal cranio-caudal (C-C) and latero-medial (L-M) directions (Fig. 1), due to specific difficulties in cutting the samples without altering the internal structure. To help cutting samples as more accurate as possible, fascia patches were put on a graph paper to follow two parallel lines with 5 mm of distance. The adipose tissue present on the surface of the superficial fascia was not totally removed, to avoid the sample breakage, and it helped maintaining the sample hydration for a longer duration. Cross-sectional area of each sample was computed by measuring both the thickness of the samples by means of a caliper (manual measures in at least three points randomly chosen on the sample) and the width from pictures taken once the sample was mounted on the machine, through the free software ImageJ (Rasband, n. d.) (five points of measure). These values were taken immediately before the experimental test, and resulted in an average width $4.63 \pm 0.89 \text{ mm}$ and thickness 0.74 ± 0.07 . Samples were hydrated with saline solution during all the time prior the mechanical testing, and then removing from the solution few minutes (no more than 5) before the test. This approach was adopted for all the samples, to provide the same conditions. Since stress-relaxation tests needed a more extended time for the relaxation, (about 30 min) samples were also hydrating through pipetting or even spraying saline solution directly on the samples, every 5 min during the test. Room temperature was monitored, ranking from 22 °C to 25 °C.

2.2. Mechanical testing

Tests were performed between May 2022 and May 2023 at the Laboratory of the Mechanics of Biological Materials, University of Padova (IT). The laboratory is equipped with a mechanical tester Model Mach-1, ©Biomomentum Inc., Laval, QC, Canada, employed for this experimental campaign. The tester setup was set to perform uniaxial tensile tests, thus formed by two stainless steel “C” shaped rough grips, which enhanced adherence to the sample surface when tight. The chosen monoaxial load cell had a capacity of 250 N and accuracy of $\pm 0.0125 \text{ N}$, 10 Hz sampling rate.

To avoid slippage, the two extremities of each rectangular strip were fixed to the sample holder by means of a commercial superglue and Velcro. The specimens were aligned into the gripping mechanism and the initial length was measured ($19.46 \pm 1.09 \text{ mm}$).

A total of 69 samples were successfully tested (42 from the abdomen, 27 from the thorax), following two different protocols: failure tests (20 from the abdomen and 15 from the thorax) and stress-relaxation tests (22 from the abdomen and 12 from the thorax). Samples that exhibited a non-clear behavior (i.e., a sample that broke at the level of the machine grips) were not included in this work. Since no mechanical tests have been reported in literature concerning the superficial fascia, the protocols were chosen with reference to a previous work on fascia lata by the authors (Bonaldi et al., 2023a). This choice could also facilitate results comparison with deep fascia. Specifically, for all the tests pre-conditioning was performed, by applying 10 cycles of loading-unloading from 0 to 4% with a strain rate of $2\% \text{ s}^{-1}$ and 15 s of resting time followed before failure or stress-relaxation protocol. This strain interval corresponded to the end of the uncrimping region, thus it did not cause any breakage to the samples. Failure tests were performed with a strain rate of $1\% \text{ s}^{-1}$, while stress-relaxation was realized by applying a strain incremental ramp (5% each up to 25% of final strain, $15\% \text{ s}^{-1}$), then maintaining the imposed strain for 300 s.

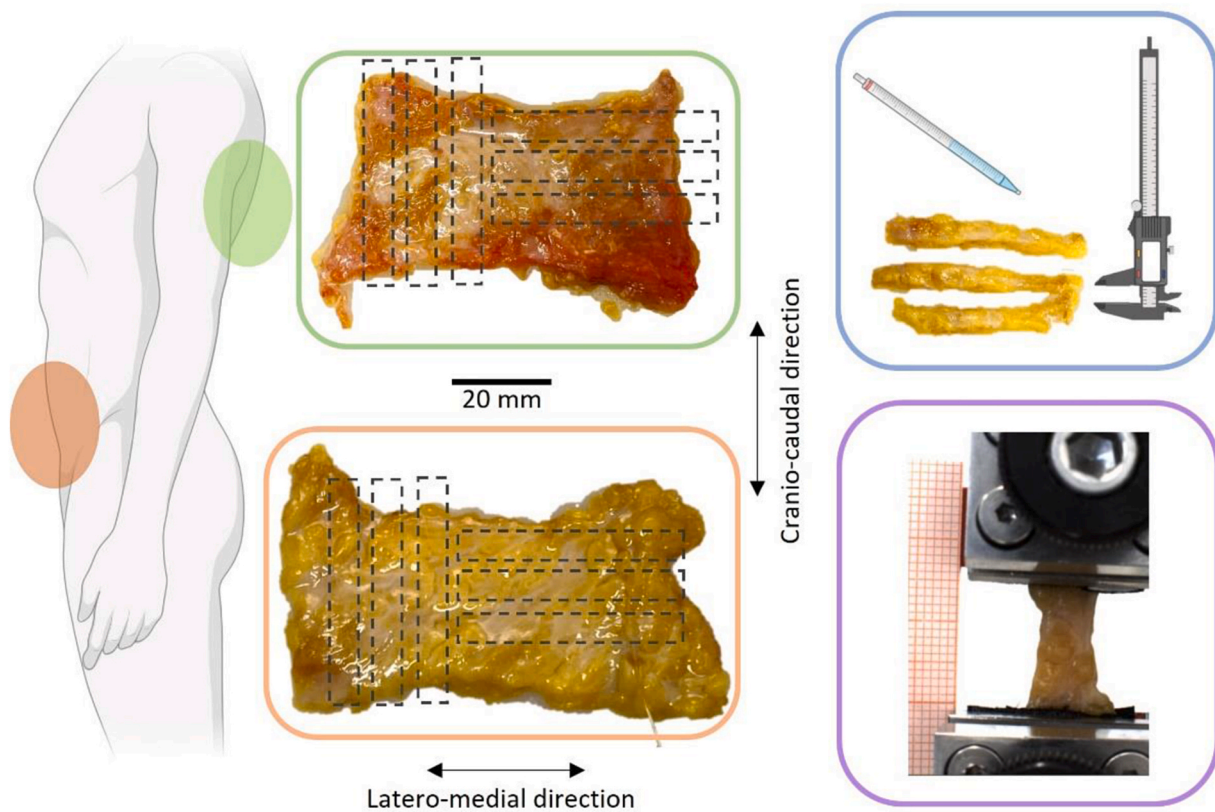


Fig. 1. (Left) Harvested patches: body regions (abdomen and posterior chest). (Middle) Sample cutting into rectangular strips according two orthogonal directions (cranio-caudal and latero-medial). (Right) Specimens hydration and mounting on mechanical tester. Created with [BioRender.com](https://www.biorender.com).

2.3. Statistical analysis

Before evaluating possible correlations, outliers were discarded following the exclusion criteria such as slippage, damage (i.e., excessive drying during testing) or rupture near grips. Results obtained from the mechanical tests were analyzed with MATLAB 2023b (“The MathWorks, Inc., MATLAB and Statistics, Natick, Massachusetts, United States,” n. d.). After checking normal distribution through the Anderson-Darling test, to evaluate the potential difference in tissue mechanical behavior according to different directions and sites, a statistical analysis was performed using Minitab Statistical Software (“Software, Minitab, State College, Pennsylvania, 2010 Minitab, Inc.,” n. d.) in terms of descriptive and inferential statistics (hypothesis tests: two-sample *t*-test, level of significance $\alpha = 0.05$ or $\alpha = 0.1$, when specified).

3. Results

Uniaxial tensile tests up to failure were realized to describe the non-linear elastic behavior of the soft tissues, while stress-relaxation protocol was performed to obtain the viscous contribution.

3.1. Failure tests

Through monitoring of load versus deformation, the stress-strain relationship was obtained by computing the nominal stress (e.g., the load normalized by the initial cross-sectional area) and the nominal strain (e.g., the elongation normalized by the initial length of each sample), as shown in Fig. 2. Then, direct quantities were extracted, such as the ultimate tensile strength (UTS), and the corresponding strain at failure (ϵ_f).

Indirect measures included the Young’s modulus (E), identified as the slope of the curve from the almost linear part, as shown in Fig. 3c

(ranking on average between $16\% \pm 5\%$ and $29\% \pm 8\%$ strain, depending on the sample), and the toughness (T), which represents the energy per unit volume a material can absorb before breakage, computed from the stress-strain curve as follows:

$$T = \int_0^{\epsilon_f} \sigma d\epsilon$$

When focusing on a single anatomical site, superficial fascia reported a significant difference between C-C and L-M directions for both the UTS and E (abdomen: *p*-value 0.029 for UTS and 0.019 for E ; thorax: *p*-value 0.033 for UTS and 0.087 for E). In both cases, the L-M direction appeared the stiffer (Fig. 3d), with a Young’s modulus that almost double with respect to the C-C direction. No significant difference was observed for the strain at break, which however resulted on average of about 45.5% for the abdominal fascia and 39% for the thoracic fascia (Fig. 3 and Table 1).

3.2. Stress-relaxation tests

The viscoelastic response of the tissue during relaxation tests was assessed by examining the normalized stress (stress divided by the peak stress value at the onset of the relaxation process) over time.

Fig. 4 illustrates the normalized median stress curves in time, with a 50% confidence interval. No significant differences were observed in the stress decay between directions and districts. Approximately 50% of the stress decay occurred within the initial 60 s, with an additional 10% on average distributed over the remaining 240 s. By the end of the relaxation period (300 s), the superficial fascia had reached an equilibrium stress level of approximately 37% of the peak stress. To maximize the quality of the fit ($R^2 > 0.80$) as well as to minimize the number of parameters, relaxation curves were fitted with a two-term Prony series (usually adopted for a variety of biological tissues (Berardo et al., 2024;

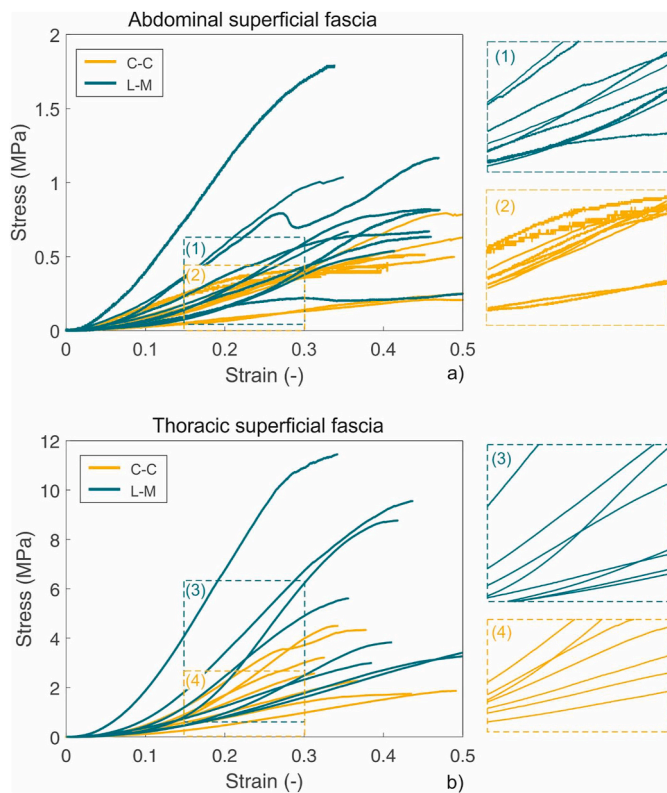


Fig. 2. Failure tests of superficial abdominal and thoracic fascia. (a) Stress-strain curves of the superficial fascia from the abdomen, with zooms on the linear regions of almost all the curves along the L-M (1) and C-C (2) directions. (b) Stress-strain curves of the superficial fascia from the thorax (back), with zooms on the linear regions of almost all the curves along the L-M (3) and C-C (4) directions.

Bonaldi et al., 2023a; Palacio-Torralba et al., 2015)), thus identifying the fit parameters γ_1 and γ_2 , τ_1 and τ_2 as follows:

$$\sigma_{norm} = \frac{\sigma(t)}{\sigma(max)} = 1 - \gamma_1 * \left(1 - e^{-\frac{t}{\tau_1}}\right) - \gamma_2 * \left(1 - e^{-\frac{t}{\tau_2}}\right)$$

Fit coefficients obtained from stress-relaxation results are reported in Fig. 4 and Table 2. Meanwhile, the comparison among equilibrium stress-strain curves (median) and failure curves (mean) for different directions and body sites is reported in Fig. 5. Each stress-strain curve was cut at 25% strain.

The comparison between failure curves and equilibrium curves is consistent with their viscoelastic behavior, since a higher strain rate (i.e., higher for the failure test than for the stress relaxation test) leads to an increase in tissue stiffness.

4. Discussions

Uniaxial tensile tests on sheet-like biological materials like the superficial fascia provide invaluable insights into their mechanical properties and implication in body structural integrity. As the material undergoes deformation, its response reveals intricate details about its composition, structure, and ability to withstand internal and external forces of daily life. With reference to the superficial fascia, anisotropic behavior was expected due to its micro- and macro-structure also in relation to the surrounding interfaces (i.e., epidermis/derma, adipose tissues, deep fascia), with differences along the body (Abu-Hijleh et al., 2006). However, differently from other fibrous tissues (e.g., deep fascia), a predominant fiber orientation was not clearly detected, and, for this reason, body planes (according to cranio-caudal and latero-medial

axes) were adopted to observe their dependence on the loading direction.

Failure tests confirmed tissue anisotropy, revealing a stiffer and tougher nature of the tissue when loaded along the L-M direction compared to the C-C one, for both the districts, even if no clear differences were observed during the rupture along the two directions. This observation is also supported by the findings of Abu-Hijleh et al., 2006, where they reported a typical appearance of superficial abdominal fascia with a well-defined fascial sheet with almost horizontal orientation of the collagen fibers obtained through polarizing light, similarly to the first fascia layer of the back region. Thus, more resistance and load support is provided by the superficial fascia along the L-M direction, even with a strain at break almost independent by the loading direction thanks to the high content of elastic fibers (in a ratio 1:1 with the collagen content (Pandey et al., 2016)). Moreover, more energy per unit volume can be stored by the tissue when elongated along the L-M direction.

Numerous studies have delved into the mechanical properties of individual layers within the structure of the abdominal wall (Deeken and Lake, 2017), especially focusing on the Linea alba (Cooney et al., 2016; Gräbel et al., 2005; Hollinsky and Sandberg, 2007) or the rectus sheet (Hollinsky and Sandberg, 2007; Martins et al., 2012; van Wingerden et al., 2020), but none reported the mechanical behavior of abdominal or thoracic superficial fascia. Hammoudeh et al. (2022) reported that the posterior chest exhibits the highest average thickness of the superficial fascia layer, and on the other hand, the thoracic region exhibits lesser subcutaneous tissue and reticularis structure than the abdominal one (skin ligaments regional distribution and variation in morphology have been also discussed by Nash et al. (2004)). This observation aligns with the fact that the skin and subcutaneous tissue of the chest wall, along with the scapular region, endure significant tension due to daily activities. They have indicated that the content of superficial fascia is greater in regions of the upper trunk subjected to higher tension compared to those experiencing lower tension, such as the lower trunk (i.e., abdomen).

From a passive mechanical response, the thoracic region exhibited significantly greater strength, Young's modulus and toughness compared to the abdomen, although both regions displayed similar strain at break. The distinct load histories likely contribute to the tissue passive response to mechanical stimuli, directly influenced by its anisotropic microstructure.

Remarkably, strength values nearly maintain a 1:2 ratio between the C-C and L-M directions across both regions, as depicted in Table 1. Similarly, the Young's modulus remains consistent across the two directions, while strain exhibited uniformity. This observation lends support to the hypothesis that, despite absolute variations in collagen and elastin content, their ratio remains constant between the two regions, as well as the principal fibers orientation. Consequently, this aspect is highlighted by the mechanical quantities such as the stress components along the two orthogonal directions, as well as on the Young's modulus. Consistent to the current study, Cooney et al. (2016), after mechanical tests on the Linea alba, observed that the transversal (i.e., L-M) direction was stiffer than the longitudinal (i.e., C-C), even with a more pronounced anisotropic behavior. Hollinsky et al. (Hollinsky and Sandberg, 2007) investigated the differences between healthy and scar tissues, observing a decrease in the load-bearing capacity of scar tissues of about 30%, with the greatest difference along the L-M direction. Furthermore, they also reported the highest values of strength along the L-M direction with respect to the C-C one.

Stress-relaxation tests highlighted the viscous behavior of the superficial fascia, with no significant differences in the stress decay between directions and districts. Indeed, the majority of the stress decay occurred within the first minute of resting time, reaching on average a 37% of residual stress after 300 s. Stress-relaxation on other fascial tissues such as fascia lata reported a higher residual stress after both 60 s (56%) and 300 s (43%) (Bonaldi et al., 2023a). Also in the latter case, the

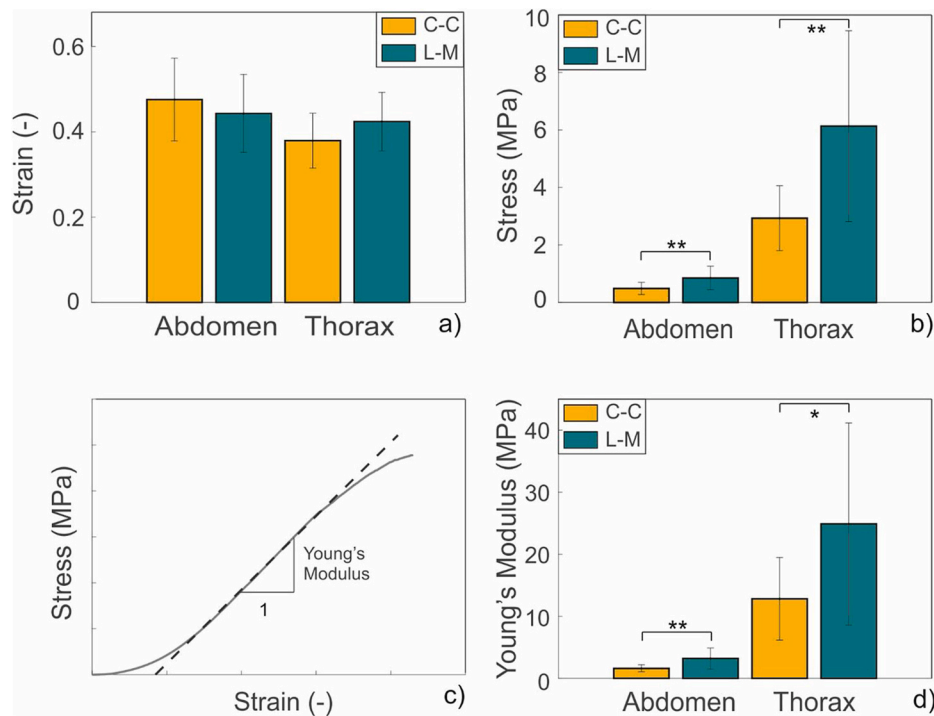


Fig. 3. (a) Strain at failure of the two regions and directions, identified as the maximum reached strain before load decreasing and sample failure. (b) UTS of the two regions and directions, identified as the maximum load normalized by the initial cross-sectional area of each sample. ** identifies a level significance equal to 0.05. (c) An example of a stress-strain curve and the Young's modulus identification, obtained as the slope of the linear region. (d) Young's modulus of the two regions and directions. ** identifies a level significance equal to 0.05, * identifies a level of significance equal to 0.1.

Table 1

UTS, strain at break and Young's modulus obtained from the uniaxial tensile tests up to failure, for abdominal and thoracic (back) superficial fascia.

FAILURE RESULTS	N	UTS (MPa)	Ratio (C-C/L-M)	Strain UTS (mm/mm)	Ratio (C-C/L-M)	E (MPa)	Ratio (C-C/L-M)	Toughness (MPa)
ABD C-C	10	0.49 ± 0.20	0.58	0.47 ± 0.09	1.07	1.61 ± 0.54	0.50	0.12 ± 0.07
ABD L-M	10	0.85 ± 0.39		0.44 ± 0.09		3.19 ± 1.62		0.17 ± 0.07
p-value (two sample t-test)		0.029		0.475		0.019		
THX C-C	7	2.93 ± 1.04	0.48	0.38 ± 0.06	0.88	12.82 ± 6.16	0.52	0.46 ± 0.16
THX L-M	8	6.13 ± 3.11		0.43 ± 0.06		24.87 ± 15.23		1.08 ± 0.56
p-value (two sample t-test)		0.033		0.205		0.087 ^a		

Globally, superficial fascia from the abdomen resulted softer than thoracic fascia, with material stiffness (*p*-value 0.004 C-C direction and 0.007 L-M direction) and maximum stress (*p*-value 0.001 C-C direction and 0.003 L-M direction) of one order of magnitude greater for this latter district. Strain at break appears significantly different only concerning the C-C direction (*p*-value 0.029).

^a Level of significance $\alpha = 0.1$.

difference in decay between directions was not found to be statistically significant. This can be again correlated to the elastic fibers content, higher in the superficial fascia than deep one (i.e., fascia lata) (Pirri et al., 2022). Other studies also investigated the viscoelastic properties of the fascial tissues, such as (Levillain et al., 2016) along the Linea alba, in which they studied non-linearity and anisotropy of the tissue following the same loading directions. The current results agree with this latter study also when considering the equilibrium stress-relaxation curves.

In conclusion, it can be suggested that, according to mechano-transduction phenomena, the content of superficial fascia may vary proportionally to the daily tension exerted on different body regions during daily activities, as also observed previously (Benjamin et al., 2008). Therefore, these findings enrich the knowledge about superficial fascia, supporting site-specific intervention such as e.g., subcutaneous suturing technique to decrease the wound tension (Hammoudeh et al., 2022).

Anyway, to fully understand the current work it is necessary to also include the limitations of the experimental results. First, biological samples are characterized by significant variability and, unfortunately,

the limited number of subjects do not present further correlation even with anthropometric data. To reduce operator-induced variability on samples cross-sectional area, future tests will be realized on samples obtained with a pre-shaped cutter. Even if a suitable and precise mechanical tester designed for biological tissues mechanical tests was adopted, strain measures could have been affected by a slightly slippage of the sample within the grips. In the future, the application of additional tools such as the Digital Image Correlation (DIC) could be useful to better monitor the sample strains. At this stage, to minimize this effect, any uncommon behavior that resulted from the acquired force led to the sample exclusion from the final set. In addition, even if the samples were thawed progressively throughout the entire test, the freeze-thaw procedure could also influence the results. Furthermore, in a future perspective, additional test protocols and settings could enrich the analysis (e.g., biaxial tests, different strain rate, etc.). Moreover, even if the histological data were supported by existing evidence in the literature (Pandey et al., 2016) further *ad hoc* analyzes could be carried out on the tested patches. Future studies will deepen the knowledge about superficial fascia composition and fibers distributions, even combined with possible difference in the breakage mechanisms along

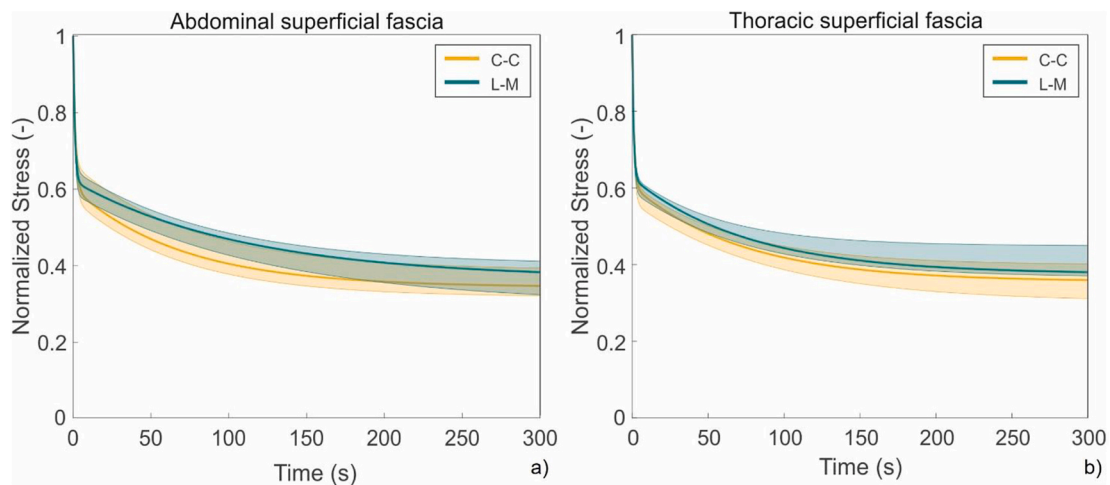


Fig. 4. Normalized stress-relaxation curves (for each ramp, of all the samples) and stress decay for both (a) abdominal (b) and thoracic (back) superficial fascia. Color bands refer to the first and third quartile.

Table 2
Residual stress and fit coefficients of a two-term Prony series.

STRESS RELAXATION RESULTS	RESIDUAL STRESS (%)			FIT COEFFICIENTS				
	After 60 s	After 240 s	After 300 s	γ_1	τ_1 (s)	γ_2	τ_2 (s)	
ABD	CC	45	35	35	0.26	69.30	0.40	1.40
	LM	52	40	38	0.25	110.00	0.38	1.03
THX	CC	47	36	36	0.25	72.40	0.39	1.17
	LM	49	39	38	0.25	76.50	0.37	0.93

these two directions. With additional experimental data, a first constitutive model could be formulated towards a computational model able to reproduce in-silico the biomechanical behavior of the superficial fascia, for personalized prevention and care.

5. Conclusions

The characterization of the human superficial fascia of different body regions, in term of tissues anisotropic and viscoelastic nature, is key to understand its in-vivo biomechanics with direct application in medical domain. Additionally, such analyses contribute to the comprehension of physiological processes and provide avenues for enhancing the durability and performance of biological structures in various applications.

Given their involvement in prevalent pathologies such as hernia repair and back pain, both the abdomen and thorax superficial fascia are frequently involved in surgical interventions or therapeutic management. Therefore, a comprehensive understanding of the mechanical attributes of superficial fascia in these regions is imperative.

Within this work, viscoelastic properties of the superficial fascia from two different anatomical districts were reported for the first time. Mechanical tests showed that the two districts have significant different behavior when subjected to the same protocol, which can be justified with the different physiological function and load history. Both revealed an anisotropic response when loaded along the cranio-caudal rather than the latero-medial direction, with this latter the stiffest. However, these results could suggest that the ratio in the fibers main components (collagen and elastin) remains constant between the two regions, as well as the principal fibers orientation. These insights paved the way for future investigations on the superficial fascia, which could also support surgical interventions and effective therapeutic modalities targeting hernias and back pain, respectively.

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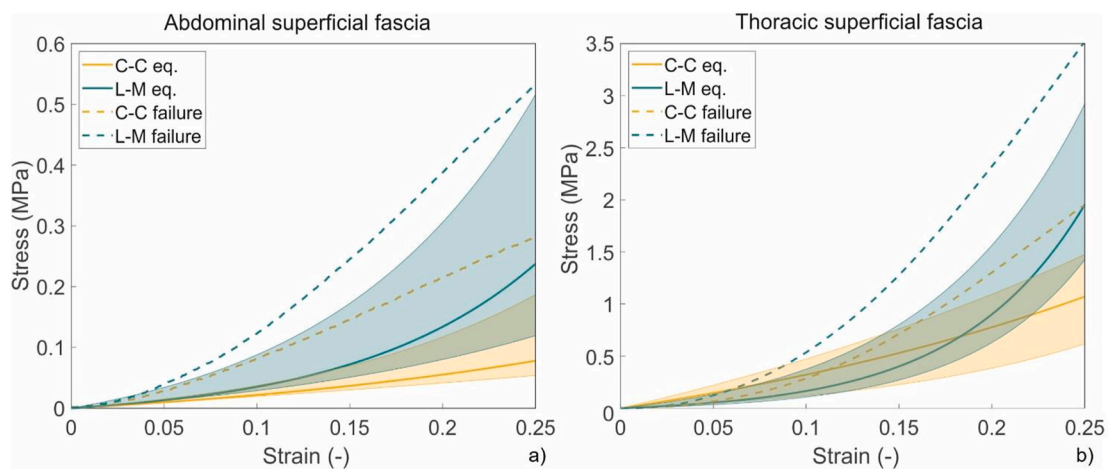


Fig. 5. Comparison among equilibrium stress-strain curves (median) and failure curves (mean) according to different directions. (a) Abdominal superficial fascia. (b) Thoracic (back) superficial fascia. Color bands refer to the first and third quartile.

CRedit authorship contribution statement

Alice Berardo: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lorenza Bonaldi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Carla Stecco:** Writing – review & editing, Visualization, Supervision, Resources, Funding acquisition, Conceptualization. **Chiara Giulia Fontanella:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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