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Morphological and Biomechanical Characterization of Early Cesarean Section Scars: A Cross-Sectional Observational Study

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Highlights

Public health relevance—How does this work relate to a public health issue?

- Cesarean scar affects recovery and quality of life.
- Early characterization of the cesarean scar reveals patterns of tissue stiffness and pain.

Public health significance—Why is this work of significance to public health?

- Shows structural and biomechanical changes in the cesarean scar.
- Supports systematic evaluation of complications related to the cesarean scar.

Public health implications—What are the key implications or messages for practitioners, policy makers and/or researchers in public health?

- Reinforces the need for early cesarean scar assessment in postpartum care.
- Guides rehabilitation strategies and integration of cesarean scar evaluation into clinical protocols.

Abstract

Cesarean section is a surgical procedure that involves the extraction of the fetus, the placenta, and the fetal membranes through an abdominal and uterine incision. As one of the most common childbirth methods worldwide, its increasing prevalence has raised concerns regarding potential postoperative sequelae that may affect tissue mobility, pain perception, and functional recovery. However, detailed characterization of early cesarean scars remains limited. This study aimed to characterize the morphological, sensory, and biomechanical properties of cesarean section scars during the early postoperative phase. A cross-sectional observational study was conducted including 20 women evaluated between 15 and 30 days after cesarean delivery. Clinical and sensory assessments were performed using the Patient and Observer Scar Assessment Scale (POSAS 3.0) and pain evaluation. Tissue mobility was assessed using a modified adheremeter, while biomechanical properties were measured with the MyotonPRO device. Ultrasound imaging was used to evaluate structural tissue characteristics. The scars predominantly exhibited increased tissue stiffness and heterogeneous texture patterns. Participants reported moderate pain intensity (mean 4.15 ± 2.18), with slightly higher scores in the patient-reported POSAS compared with the observer scale. Ultrasound findings revealed dermal and hypodermal edema in most participants and signs of fibrosis, with regional heterogeneity in tissue adhesions. Biomechanical analysis confirmed reduced tissue deformability in scar tissue

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compared with adjacent healthy tissue. These findings indicate that early cesarean scars present relevant structural and functional alterations, highlighting the importance of early assessment to support individualized rehabilitation strategies.

Keywords: cesarean section; surgical scar; scar biomechanics; tissue adhesions; physiotherapy

1. Introduction

Cesarean section is a surgical procedure that involves the extraction of the fetus through an abdominal and uterine incision and represents one of the most common childbirth methods worldwide. Although the procedure is sometimes essential to preserve maternal and fetal health, its increasing prevalence has raised concerns regarding potential long-term consequences for women's health [1,2].

The scars resulting from cesarean section may alter the architecture of the fascia and restrict sliding between tissue layers, contributing to pain, movement limitations, and muscular dysfunction (Figure 1) [3,4]. Scar formation following cesarean delivery is also frequently associated with the development of adhesions, defined as fibrous bands of scar tissue that form between intra-abdominal structures and organs. These adhesions may restrict organ mobility, cause chronic abdominal or pelvic pain, infertility, and increased risk of complications in subsequent abdominal surgeries [5,6].

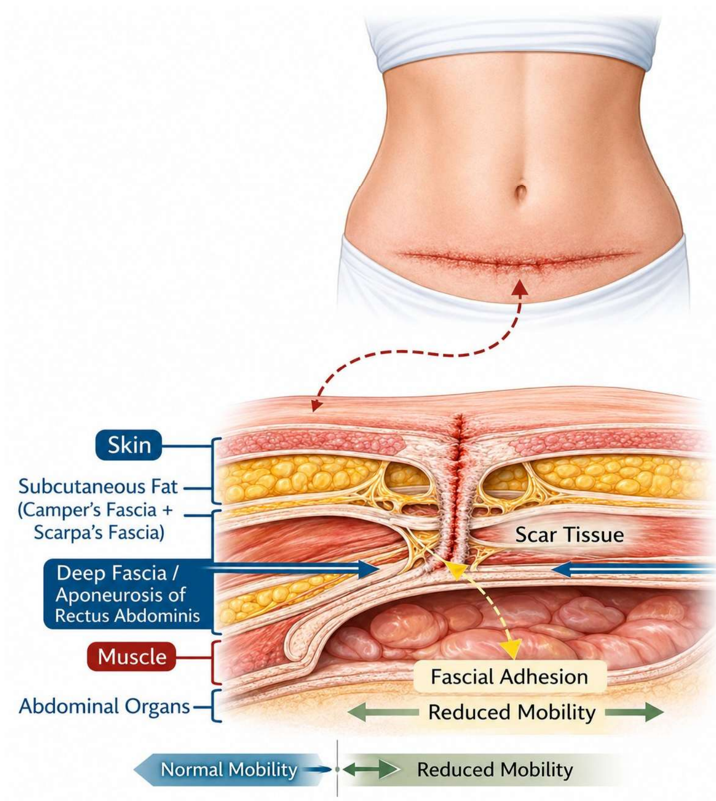

Figure 1. Schematic representation of cesarean section scar formation and its potential effects on the abdominal wall. The illustration highlights the anatomical layers of the abdominal wall and the development of scar tissue and fascial adhesions that may contribute to reduced tissue mobility. Source: Image generated by ChatGPT—version GPT-4o, OpenAI and modified/labeled by the authors.

The early postoperative period, typically between 15 and 30 days after cesarean section, is characterized by intense proliferative activity and the initiation of tissue remodeling processes [7,8]. During this phase, granulation tissue formation occurs, with fibroblast proliferation, collagen deposition, and neovascularization, which are essential processes for structural tissue repair [8,9]. The interaction between fibroblasts and myofibroblasts plays a key role in extracellular matrix formation and directly influences the final quality of the scar [9].

Clinical assessment during this phase may positively influence healing outcomes by identifying alterations in collagen deposition, preventing pathological scars or excessive adhesions, and addressing early changes in fascial integrity and tissue biomechanics [10,11]. Furthermore, given the potential adverse clinical consequences associated with surgical delivery, these findings reinforce that cesarean sections should be carefully considered and performed only under clear medical indications [12]. Considering the relevance of the early postoperative period for structural and functional tissue organization, this study aimed to characterize the morphological, sensory, and biomechanical properties of cesarean scars evaluated between 15 and 30 days post-surgery.

2. Materials and Methods

2.1. Ethical Considerations

This study was approved by the Health Ethics Committee of Hospital Particular do Algarve (No. 2/2025, approved on 18 February 2025). All participants provided written informed consent prior to participation, and the study was conducted in accordance with the principles of the Declaration of Helsinki.

2.2. Study Design

This cross-sectional study, employing within-subject paired comparisons between the scar tissue and adjacent healthy reference skin, aimed to characterize the morphological, sensory, and biomechanical properties of cesarean section scars during the early postoperative period. The study followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines (Table S1) [13]. Evaluations were performed during the early postoperative phase following cesarean delivery. All procedures were performed by four institutional surgeons using a standardized technique, and follow-up assessments were conducted by a single examiner.

2.3. Participants

The study was conducted between March and June 2025. During the screening phase, 59 pregnant women underwent a standardized anamnesis. To avoid baseline confounding factors, only non-smokers, alcohol abstainers, and patients without pregestational or gestational diabetes mellitus were eligible for consideration. Out of the initial group, 39 women were excluded: 33 due to postoperative infection, hematoma, or persistent seroma, and 6 who declined participation. The final sample comprised 20 women who underwent elective cesarean delivery and completed the early postoperative postpartum follow-up.

Inclusion criteria were: age between 18 and 45 years, good general health status, body mass index between 18.5 and 30 kg/m^2, and the ability to understand and sign the informed consent form.

Exclusion criteria included the presence of wound infection, hematoma requiring intervention, persistent seroma, partial or total wound dehiscence, necrosis in the incision area, or dermatological conditions affecting the scar region.

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2.4. Clinical and Scar Assessment

Scar assessment was performed in a single session by a trained investigator, including clinical, sensory, and biomechanical analyses. To evaluate spatial heterogeneity a priori, three standardized points were defined: the central point C (linea alba/midline, subject to distinct fascial tension) and lateral extremities D and E. Quality of life was assessed using the 10-item Dermatology Life Quality Index (DLQI; score 0–30; categorized as 0–5 minimal, 6–10 moderate, and 11–30 severe impact) [14]. Pain intensity at rest and movement was measured using an 11-point Numeric Rating Scale (NRS; 0 = no pain, 10 = worst pain), accompanied by standardized verbal selection of qualitative pain descriptors (e.g., burning, sharp pain) [15].

2.4.1. Scar Quality Assessment

Scar quality was evaluated using the POSAS 3.0, comprising patient (6 items) and observer (6 items) scales scored from 1 (normal skin) to 10 (worst imaginable scar), yielding subscale totals of 6–60, where higher scores indicate worse scar quality. The patient scale assesses subjective symptoms (e.g., pain, itch, appearance), while the observer scale measures objective characteristics (e.g., pigmentation, vascularization, thickness, pliability) [16].

2.4.2. Tissue Extensibility

Scar tissue extensibility and adhesion were evaluated using a modified adheremeter, a non-invasive instrument designed to quantify skin mobility [17]. The device was adapted from the model proposed by Ferriero et al. (2010) and consists of a flexible transparent plate with concentric rings that allow visualization and measurement of skin displacement [18]. The modified adheremeter quantifies global cutaneous displacement over underlying structures, without isolating the specific anatomical depth or fascial layer responsible for tissue restriction.

The device features a flexible transparent circular plate with concentric rings to measure global skin displacement in four orthogonal directions (superior, inferior, left, right) at points C, D, and E. To optimize contact over extended cesarean scars, a modified plate with a 4.6 cm radius (9.2 cm diameter) was used instead of the original 28 mm design, which alters the contact area and lever arm relative to original validation standards. Skin mobility was expressed via the Adheremeter Mobility Index (AMI), calculated as the mean displacement of the scar divided by the mean displacement of control healthy skin (AMI = Displacementscar/Displacementcontrol), yielding a normalized ratio from 0 (complete fixation) to 1 (normal mobility). All measurements were taken in triplicate by the same trained examiner applying minimal contact pressure.

2.4.3. Digital Image Analysis

Morphological characteristics of the scars were assessed using digital imaging. Photographs were analyzed using ImageJ software (version 1.54f, National Institutes of Health, Bethesda, MD, USA) to evaluate parameters such as scar area and surface irregularity [19]. Texture analysis was performed using Gray-Level Co-occurrence Matrix (GLCM) algorithms on 8-bit grayscale images (256 gray levels, range 0–255). The GLCM was computed using a pixel displacement (d) of 1 pixel across four directional angles (0°, 45°, 90°, and 135°), with directional results averaged [20]. GLCM matrices were normalized to express probability density. Textural features included angular second moment, entropy, contrast, correlation, and inverse difference moment. Digital image analysis and GLCM texture assessment exclusively evaluate the superficial epidermal/cutaneous surface (2D evaluation).

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2.4.4. Biomechanical Properties

Scar viscoelastic properties (tone, stiffness, elasticity, creep, relaxation time) were evaluated using the validated MyotonPRO (Myoton AS, Tallinn, Estonia), assessing a composite of superficial cutaneous and upper subcutaneous layers. Participants were tested in a relaxed supine position. The probe was held perpendicular (90°) to the skin along the scar's longitudinal axis. Data were acquired in multi-scan mode (5 consecutive 0.4 N impulses per burst) in triplicate at points C, D, E, and supraumbilical controls, using the mean values for analysis. The literature supports high MyotonPRO measurement reliability (ICC = 0.85–0.98) [3].

2.4.5. Ultrasound Evaluation

Ultrasound assessment was performed using a Vscan Air device (General Electric Company, Chicago, IL, USA) with a linear transducer (3–12 MHz; central frequency 7.7 MHz). Unlike surface-level tools, ultrasound provided a true multilayered structural evaluation across dermal, hypodermal, and deep fascial layers. Images acquired at points C, D, and E were captured via the device freeze-frame function and subjected to a semi-quantitative categorical evaluation (presence/absence) by a trained investigator using standardized visual criteria: edema was defined as fluid-induced dermal/hypodermal hypoechogenicity; scar tissue deposition/fibrosis as localized hyperechoic/disorganized connective tissue distortion; seroma/collections as well-defined anechoic fluid pockets; and nodular processes as circumscribed hypoechoic tissue masses [21,22].

2.5. Statistical Analysis

The sample size was calculated a priori using G*Power software (version 3.1.9.7). A two-tailed paired-samples *t*-test was specified, considering a mean difference of 1.30 mm, a standard deviation of 1.95 mm, a significance level of $\alpha = 0.05$, and statistical power of 80%. The resulting standardized effect size was Cohen's d = 0.665, indicating a moderate-to-large effect, and the minimum required sample size was 20 participants [23].

Descriptive statistics were expressed as means and standard deviations for continuous variables and frequencies for categorical variables. Data normality was assessed using the Shapiro–Wilk test. Non-parametric comparisons were performed using the Friedman test, followed by the Dunn–Conover post hoc test. Paired comparisons were conducted using the Wilcoxon signed-rank test, when appropriate. Additionally, Spearman correlation analyses were performed to investigate the associations between Observer and Patient POSAS scores, scar mobility assessed using the adheremeter, and the biomechanical parameters measured by the MyotonPRO. Statistical significance was set at $p < 0.05$. Statistical analyses were performed using Jamovi software (version 2.6.44; The Jamovi Project, Sydney, Australia).

2.6. Generative AI Use

Generative AI (ChatGPT, GPT-4o, OpenAI) was used to generate initial schematic visual concepts for Figures 1 and 2, which were subsequently modified and validated by the authors, as well as for language editing. The tool was not used for data collection, statistical analysis, or study design.

3. Results

3.1. Participant Characteristics

A total of 20 women who had undergone cesarean section during the early postoperative period (15–30 days) were included in the study. The mean age of participants was 32.25 ± 3.92 years, with a mean body mass of 63.95 ± 8.53 kg and a mean height of

1.63 ± 0.06 m. The mean body mass index was 24.17 ± 2.85 kg/m^2, corresponding to the normal weight range according to World Health Organization criteria.

Regarding surgical history, 18 participants (90%) presented only the cesarean scar, while two participants (10%) reported previous abdominal surgical scars.

The mean scar length measured during the clinical evaluation was 13.73 ± 1.43 cm, reflecting the average extension of the Pfannenstiel incision within the evaluated sample.

3.2. Pain Profile Associated with the Cesarean Scar

The mean pain intensity reported by participants was 4.15 ± 2.18, corresponding to a moderate level of pain with considerable inter-individual variability. Participants reported heterogeneous sensory characteristics and different pain-triggering conditions. Pain intensity also demonstrated a statistically significant moderate negative correlation with the postoperative assessment day (ρ = −0.48, p = 0.032). The distribution of pain characteristics, triggering factors, and temporal behavior is summarized in Figure 2.

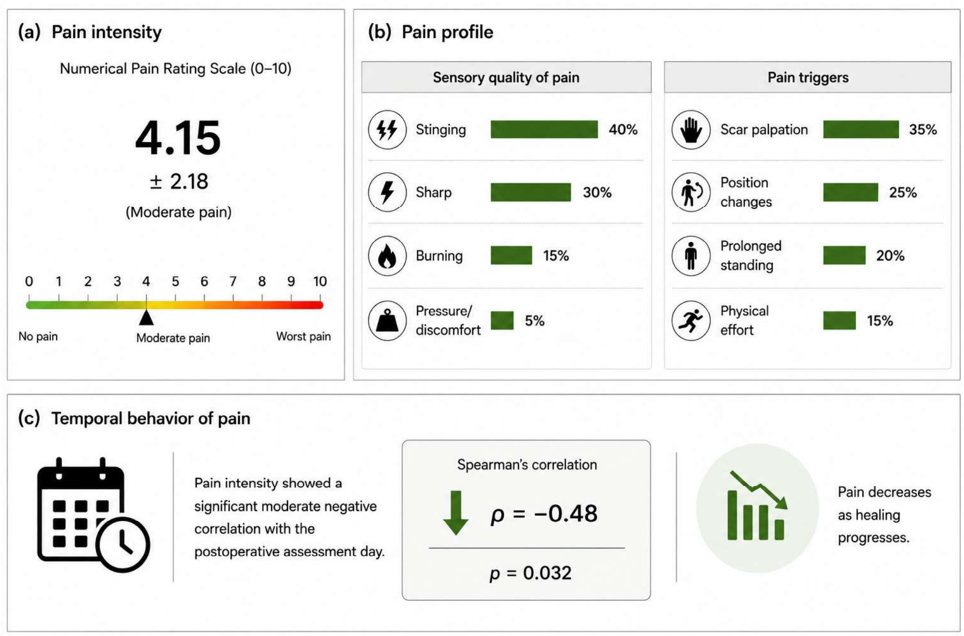

Figure 2. Pain profile associated with the cesarean scar during the early postoperative period. (**a**) Mean pain intensity assessed using the Numerical Pain Rating Scale (0–10). (**b**) Distribution of reported sensory pain characteristics and pain-triggering factors. (**c**) Relationship between pain intensity and postoperative assessment day, demonstrating a statistically significant moderate negative correlation (Spearman's ρ = −0.48, p = 0.032). Source: Image generated by ChatGPT—version GPT-4o, OpenAI and modified/labeled by the authors.

3.3. Impact of Cesarean Scar on Quality of Life

The impact of the cesarean scar on quality of life was assessed using the Dermatology Life Quality Index (DLQI). Half of the participants (50%) reported minimal or no impact of the scar on daily life.

A moderate impact was reported by 30% of participants, while 20% reported considerable or severe impact, indicating that although many women adapt well during the early postpartum period, a relevant subset experiences functional or emotional limitations related to the scar. These findings demonstrate heterogeneity in the perception of the impact of cesarean scars on daily activities and well-being.

3.4. Scar Quality Assessment (POSAS 3.0)

Scar quality was evaluated using the Patient and Observer Scar Assessment Scale, POSAS 3.0 [16], which integrates two complementary dimensions: the subjective experience reported by the patient and the clinical evaluation performed by a trained observer. This combined approach allowed the assessment of both aesthetic and functional characteristics of the scars, as well as the associated sensory and emotional experiences.

The mean score obtained on the POSAS Patient scale was 32.4 ± 6.5 points, slightly higher than the mean score recorded on the POSAS Observer scale, which was 29.7 ± 4.8 points, although no statistically significant difference was observed between the two evaluations ($p > 0.05$). This difference reflects the nature of subjective assessment, as patients report individual symptoms such as pain, sensitivity, pruritus, and sensations of tightness, which are not always fully captured through clinical observation.

The broader range of responses reported by patients (25 to 49 points) indicated considerable perceptual heterogeneity, with some women describing significant discomfort even in scars clinically classified as moderate. In contrast, scores assigned by observers showed lower variability (18 to 38 points), suggesting greater consistency in the identification of structural alterations, such as pigmentation, vascularization, texture, and firmness.

3.5. Texture Analysis of Cesarean Scars (Digital Imaging)

Texture analysis revealed substantial intra- and inter-individual variability in GLCM-derived parameters. ASM values ranged predominantly from 1 to 4 (85%), whereas entropy ranged from 5.9 to 7.9, with 90% of participants presenting values between 6.0 and 7.5. Contrast showed marked variability, with values ≤ 60 in 40% of participants, >100 in 35%, and >180 in at least one direction in 25%. Directional differences in contrast greater than 50 units were observed in 70% of participants. Correlation values ranged from 0.23 to 1.00, with values between 0.5 and 0.7 observed in 60% of participants and values ≥ 0.9 in 40%. IDM showed minor directional variation. Overall, GLCM-derived texture parameters demonstrated heterogeneous patterns across participants and directional measurements (Table 1).

Table 1. Distribution of gray-level co-occurrence matrix (GLCM)-derived texture parameters in early cesarean section scars.

Parameter	Observed Values/Pattern	*n* (%)
ASM	1–4	17 (85%)
	<1 in at least one direction	3 (15%)
Entropy	5.9–7.9	20 (100%)
	6.0–7.5	18 (90%)
	>7.8	2 (10%)
Contrast	≤60	8 (40%)
	>100	7 (35%)
	>180 in at least one direction	5 (25%)
	Directional difference > 50 units	14 (70%)
Correlation	0.23–1.00	20 (100%)
	0.5–0.7	12 (60%)
	≥0.9	8 (40%)

Abbreviations: ASM, angular second moment; GLCM, gray-level co-occurrence matrix.

3.6. Tissue Adhesion and Extensibility (Modified Adheremeter)

The mean adhesion index was 0.204 ± 0.09, with variability in tissue mobility across participants and scar regions (Figure 3). No overall difference in adhesion was observed among the right, central, and left regions (Friedman test: $\chi^2 = 5.20$; $p = 0.074$). However, post hoc analysis identified a significant difference between the central and right regions

($p = 0.026$), whereas no significant differences were observed between the left and central or left and right regions.

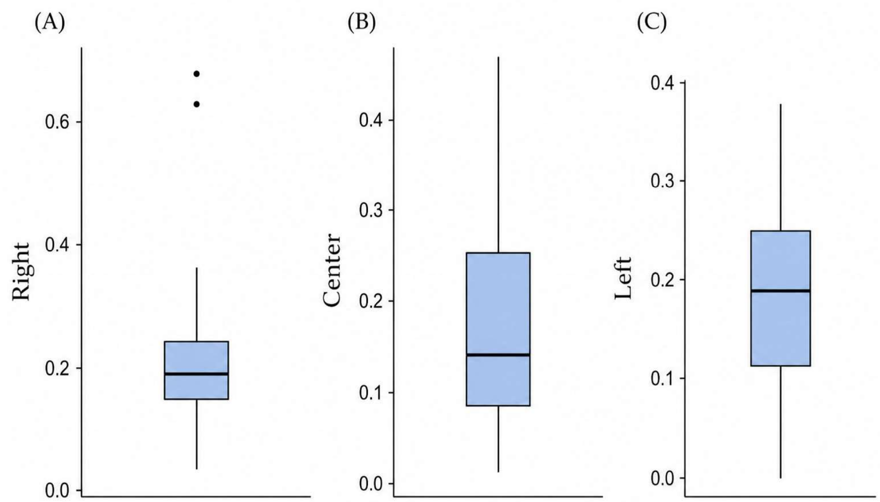

Figure 3. Distribution of adhesion indices measured with the modified adheremeter across the right (**A**), center (**B**), and left (**C**) regions of the cesarean scar. The mobility index ranges from 0 to 1, with lower values indicating greater tissue adhesion. Boxplots show the median, interquartile range, and outliers.

3.7. Viscoelastic Properties of the Scar Tissue

Biomechanical assessment revealed region-dependent differences between cesarean scar tissue and intact abdominal skin (Table 2). The central region showed the greatest number of significant differences, with lower Creep and Relaxation Time and higher Frequency and Stiffness in scar tissue (all $p < 0.001$), while Logarithmic Decrement did not differ significantly ($p = 0.344$).

Table 2. Comparison of viscoelastic parameters between cesarean scar tissue and intact abdominal skin according to scar region. *p*-values correspond to comparisons between scar tissue and intact skin for each biomechanical parameter and measurement region. Statistical significance was set at $p < 0.05$.

Scar Region	Parameter	*p*-Value
Central	Creep	<0.001
	Frequency	<0.001
	Stiffness	<0.001
	Relaxation Time	<0.001
	Logarithmic Decrement	0.344
Right	Creep	>0.05
	Frequency	<0.001
	Stiffness	<0.001
	Relaxation Time	0.047
	Logarithmic Decrement	>0.05
Left	Creep	>0.05
	Frequency	0.003
	Stiffness	0.052
	Relaxation Time	>0.05
	Logarithmic Decrement	>0.05

In the right region, Frequency and Stiffness were significantly higher in scar tissue (both $p < 0.001$), whereas Relaxation Time was lower ($p = 0.047$). No significant differences were observed for Creep or Logarithmic Decrement. In the left region, only Frequency differed significantly ($p = 0.003$), with higher values in intact skin. The remaining parameters showed no significant differences, although Stiffness approached statistical significance ($p = 0.052$).

Spearman correlation analyses showed no significant associations between Observer or Patient POSAS scores, texture contrast, or scar mobility and the biomechanical parameters measured by the MyotonPRO (all $p > 0.05$; Table 3).

Table 3. Spearman correlations between clinical scar assessment, digital texture analysis, scar mobility, and biomechanical properties of early cesarean section scars. Values are presented as Spearman's correlation coefficient (ρ) with corresponding *p*-values.

Variable	Frequency	Stiffness	Logarithmic Decrement	Relaxation Time	Creep
Observer POSAS score	−0.197 (0.405)	−0.072 (0.764)	0.134 (0.572)	0.023 (0.924)	0.073 (0.760)
Patient POSAS score	−0.225 (0.341)	−0.136 (0.568)	0.134 (0.573)	0.229 (0.332)	0.248 (0.292)
Texture contrast	−0.003 (0.990)	−0.240 (0.308)	−0.141 (0.552)	0.156 (0.512)	−0.072 (0.762)
Scar mobility	−0.189 (0.424)	−0.228 (0.333)	−0.277 (0.237)	0.306 (0.189)	0.179 (0.449)

3.8. Ultrasound Evaluation of the Cesarean Scar

Ultrasound evaluation revealed a heterogeneous structural profile, with edema and scar tissue deposition as the most frequent findings, followed by anechoic cysts and seromas (Figure 4). Dermal and hypodermal edema was frequently associated with lymphatic congestion and disorganization of the subcutaneous septa, occasionally extending to deeper tissue layers. Fibrotic changes were characterized by hyperechoic foci and areas of dense connective tissue.

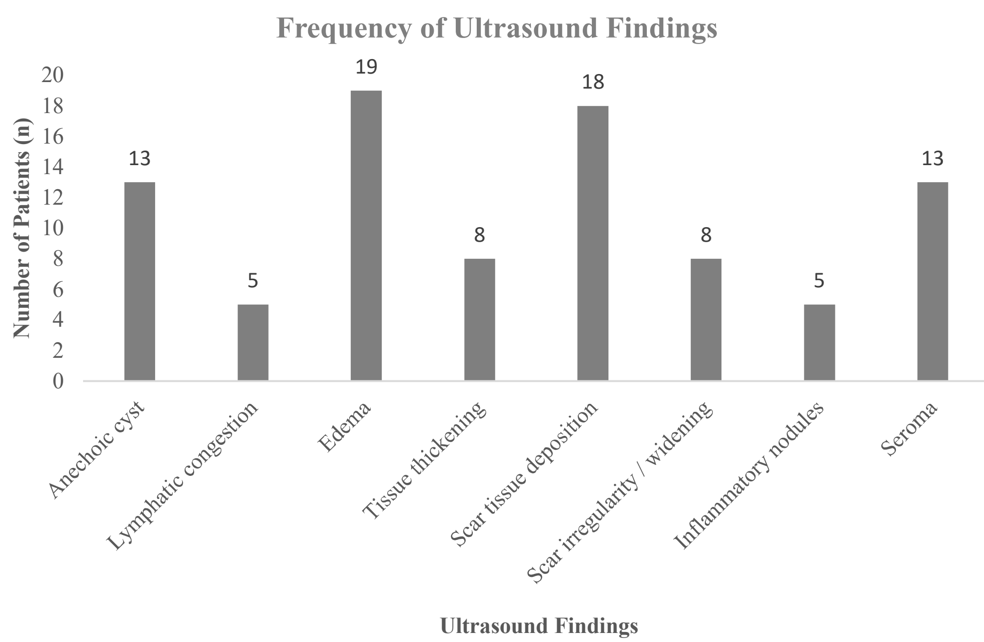

Figure 4. Frequency of ultrasound findings observed in cesarean section scars. The bars represent the number of patients presenting each finding. The most frequent alterations were edema ($n = 19$) and scar tissue deposition ($n = 18$), followed by anechoic cyst and seroma ($n = 13$ each).

Regional analysis showed more pronounced structural alterations in the central portion of the scar, particularly edema, deeper seromas, and fibrotic areas, whereas the lateral regions showed comparatively fewer alterations. Fluid collections, tissue thickening, scar irregularity, and inflammatory nodular changes were also observed, although less frequently.

Ultrasonographic evaluations during the 15–30 day postoperative period (mean: 21.5 ± 4.1 days) predominantly revealed dermal and hypodermal edema, accompanied by early fibrotic remodeling, fluid collections, and occasional nodular inflammatory changes. Overall, these findings reflect a dynamic, transitional phase of scar healing, in which structural characteristics vary according to the precise timing of measurement.

4. Discussion

The present study characterized cesarean section scars during the early postoperative period (15–30 days) through a multidimensional assessment of clinical symptoms, scar quality, biomechanical properties, tissue mobility, texture, and ultrasonographic findings. Overall, the findings demonstrate substantial heterogeneity in structural organization, mechanical behavior, and sensory perception during early scar remodeling.

Pain showed considerable interindividual variability and was frequently associated with mechanical stimuli such as palpation, changes in body position, and physical effort, suggesting the contribution of both inflammatory and biomechanical mechanisms. Extracellular matrix organization and mechanotransduction pathways are recognized as important regulators of nociceptive activation and tissue remodeling following surgical injury [8,9].

Patient-reported scar assessment highlighted greater concerns regarding overall appearance and color, whereas pain, hypersensitivity, and movement-related tension showed greater variability. Observer assessment predominantly identified firmness, adhesion, and tissue tension. Although patient and observer evaluations were generally comparable, patients tended to perceive greater scar severity, reinforcing the complementary value of incorporating both perspectives into scar assessment.

Texture analysis revealed substantial variability in GLCM-derived parameters, reflecting heterogeneous superficial organization within and between scars. Lower contrast and intermediate entropy associated with higher ASM and IDM are consistent with more homogeneous surface patterns during early remodeling [20]. Conversely, higher entropy and contrast may reflect greater structural heterogeneity associated with extracellular matrix disorganization and persistent fibroblast activity [9,20]. These observations are consistent with mechanobiological models in which fibroblast differentiation and collagen deposition are influenced by mechanical stress within the tissue microenvironment [24].

Directional variability was observed in approximately 70% of participants, supporting the presence of anisotropic scar organization. Such behavior may reflect disruption of native dermal collagen architecture following surgical incision, as physiological collagen orientation follows mechanical tension lines and contributes to the anisotropic properties of skin [25].

Scar mobility assessment demonstrated regional variability, with post hoc analysis identifying a difference between the central and right regions despite the absence of a significant overall regional effect. This heterogeneity may be influenced by surgical technique, local tension distribution, and patient-specific movement patterns [10,17]. Scar adhesions can impair fascial gliding and tissue mobility, potentially contributing to altered postoperative biomechanics and localized discomfort [17,18].

Biomechanical assessment further demonstrated region-dependent differences between scar tissue and intact skin, particularly in the central region, where increased stiffness and tone were accompanied by reduced creep and relaxation time [3]. Increased stiffness and reduced deformability are compatible with changes in collagen density and extracellular matrix cross-linking during early remodeling [8,24], potentially affecting tissue compliance and mechanical adaptability.

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Ultrasonography complemented these findings by demonstrating frequent dermal and hypodermal edema, lymphatic congestion, septal disorganization, and fibrotic alterations, supporting ongoing extracellular matrix remodeling during this postoperative period [21,22]. Fluid collections were also observed, while structural abnormalities occasionally extended into deeper connective tissues and the muscular plane, emphasizing the three-dimensional nature of cesarean scar remodeling.

Taken together, the structural, biomechanical, imaging, and sensory findings characterize the early cesarean scar as a heterogeneous and dynamic tissue undergoing active remodeling. These findings support multidimensional scar assessment as a means of capturing features that may not be adequately represented by clinical inspection alone and may contribute to the development of more targeted strategies for postoperative recovery.

Study limitations include the use of supraumbilical skin as a reference region to minimize interference from postoperative edema, although anatomical differences in dermal thickness and tension between abdominal regions may remain. The cross-sectional assessment captures scar characteristics at a single early postoperative stage and does not establish their longitudinal evolution. Finally, semi-quantitative ultrasonographic assessments were performed by a single trained investigator, and future studies should evaluate inter-examiner reproducibility and longitudinal changes.

5. Conclusions

Cesarean section scars in the early postoperative period exhibit morphological, sensory, textural, and biomechanical alterations, with substantial heterogeneity across individuals and scar regions. These findings highlight the complexity of early scar remodeling and the value of multidimensional assessment integrating clinical, biomechanical, and imaging-based measures. As an exploratory characterization, this study provides a baseline for understanding early cesarean scar dynamics and generates hypotheses for future longitudinal and interventional studies investigating scar evolution and rehabilitation strategies in postpartum women.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ijerph23091179/s1, Table S1: STROBE Statement—Checklist of items that should be included in reports of cross-sectional studies.

Author Contributions: Conceptualization, L.K., C.M.R.P. and E.C.d.O.G.; methodology, L.K. and C.M.R.P.; validation, L.K., C.M.R.P., A.C.P.d.M. and A.N.; formal analysis, L.K. and C.M.R.P.; investigation, L.K. and C.M.R.P.; data curation, L.K. and C.M.R.P.; writing—original draft preparation, L.K. and C.M.R.P.; writing—review and editing, A.C.P.d.M., A.N., A.P.F. and E.C.d.O.G.; visualization, L.K. and C.M.R.P.; supervision, E.C.d.O.G.; project administration, E.C.d.O.G.; funding acquisition, E.C.d.O.G. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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for the purposes of generating initial schematic concepts for Figures 1 and 2, as well as language refining. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ASM	Angular Second Moment
DLQI	Dermatology Life Quality Index
GLCM	Gray-Level Co-occurrence Matrix
ICC	Intraclass Correlation Coefficient
IDM	Inverse Difference Moment
POSAS	Patient and Observer Scar Assessment Scale

References

1. Keag, O.E.; Norman, J.E.; Stock, S.J. Long-term risks and benefits associated with cesarean delivery for mother, baby, and subsequent pregnancies: Systematic review and meta-analysis. *PLoS Med.* **2018**, *15*, e1002494. [CrossRef]
2. Clark, E.A.; Silver, R.M. Long-term maternal morbidity associated with repeat cesarean delivery. *Am. J. Obstet. Gynecol.* **2011**, *205*, S2–S10. [CrossRef]
3. Gilbert, I.; Gaudreault, N.; Gaboury, I. Intra- and inter-evaluator reliability of the MyotonPRO for the assessment of the viscoelastic properties of caesarean section scar and unscarred skin. *Ski. Res. Technol.* **2021**, *27*, 370–375. [CrossRef]
4. Wasserman, J.B.; Copeland, M.; Upp, M.; Abraham, K. Effect of soft tissue mobilization techniques on adhesion-related pain and function in the abdomen: A systematic review. *J. Bodyw. Mov. Ther.* **2019**, *23*, 262–269. [CrossRef]
5. Awonuga, A.O.; Fletcher, N.M.; Saed, G.M.; Diamond, M.P. Postoperative adhesion development following cesarean and open intra-abdominal gynecological operations: A review. *Reprod. Sci.* **2011**, *18*, 1166–1185. [CrossRef]
6. Practice Committee of the American Society for Reproductive Medicine. Postoperative adhesions in gynecologic surgery: A committee opinion. *Fertil. Steril.* **2019**, *112*, 458–463. [CrossRef]
7. Debras, E.; Capmas, P.; Maudot, C.; Chavatte-Palmer, P. Uterine wound healing after caesarean section: A systematic review. *Eur. J. Obstet. Gynecol. Reprod. Biol.* **2024**, *296*, 83–90. [CrossRef]
8. Gurtner, G.C.; Werner, S.; Barrandon, Y.; Longaker, M.T. Wound repair and regeneration. *Nature* **2008**, *453*, 314–321. [CrossRef]
9. Micallef, L.; Vedrenne, N.; Billet, F.; Coulomb, B.; Darby, I.A.; Desmoulière, A. The myofibroblast, multiple origins for major roles in normal and pathological tissue repair. *Fibrogenesis Tissue Repair* **2012**, *5*, S5. [CrossRef]
10. Michalska, A.; Mierzwa-Molenda, M.; Bielasik, K.; Pogorzelska, J.; Wolder, D.P.; Swiercz, G. Optimization of the cosmetic appearance of skin scar after caesarean section—Part II physiotherapy practice. *Ginekol. Pol.* **2024**, *95*, 156–166. [CrossRef]
11. Wolder, D.P.; Swiercz, G.M.; Michalska, A.; Pogorzelska, J. Optimization of the cosmetic appearance of skin scar after caesarean section—Part I: Obstetric practice. *Ginekol. Pol.* **2023**, *94*, 754–758. [CrossRef]
12. World Health Organization. *WHO Statement on Caesarean Section Rates*; World Health Organization: Geneva, Switzerland, 2015.
13. von Elm, E.; Altman, D.G.; Egger, M.; Pocock, S.J.; Gøtzsche, P.C.; Vandenbroucke, J.P. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) Statement: Guidelines for reporting observational studies. *PLoS Med.* **2007**, *4*, e296. [CrossRef]
14. Finlay, A.Y.; Khan, G.K. Dermatology Life Quality Index (DLQI)—A simple practical measure for routine clinical use. *Clin. Exp. Dermatol.* **1994**, *19*, 210–216. [CrossRef]
15. Hawker, G.A.; Mian, S.; Kendzerska, T.; French, M. Measures of adult pain: Visual Analog Scale for Pain (VAS Pain), Numeric Rating Scale for Pain (NRS Pain), McGill Pain Questionnaire (MPQ), Short-Form McGill Pain Questionnaire (SF-MPQ), Chronic Pain Grade Scale (CPGS), Short Form-36 Bodily Pain Scale (SF-36 BPS), and Measure of Intermittent and Constant Osteoarthritis Pain (ICOAP). *Arthritis Care Res.* **2011**, *63*, S240–S252. [CrossRef]
16. Carrière, M.E.; Mokkink, L.B.; Tyack, Z.; Westerman, M.J.; Pijpe, A.; Pleat, J.; van de Kar, A.L.; Brown, J.; de Vet, H.C.W.; van Zuijlen, P.P.M. POSAS 3.0 Development Group. Development of the Patient Scale of the Patient and Observer Scar Assessment Scale (POSAS) 3.0: A qualitative study. *Qual. Life Res.* **2023**, *32*, 583–592. [CrossRef]
17. Kelly-Martin, R.; Doughty, L.; Garkavi, M.; Wasserman, J.B. Reliability of modified adheremeter and digital pressure algometer in measuring normal abdominal tissue and C-section scars. *J. Bodyw. Mov. Ther.* **2018**, *22*, 972–979. [CrossRef]
18. Ferriero, G.; Vercelli, S.; Salgovic, L.; Stissi, V.; Sartorio, F. Validation of a new device to measure postsurgical scar adherence. *Phys. Ther.* **2010**, *90*, 776–783. [CrossRef]

19. Schneider, C.A.; Rasband, W.S.; Eliceiri, K.W. NIH Image to ImageJ: 25 years of image analysis. *Nat. Methods* **2012**, *9*, 671–675. [CrossRef]
20. Haralick, R.M.; Shanmugam, K.; Dinstein, I. Textural features for image classification. *IEEE Trans. Syst. Man Cybern.* **1973**, *SMC-3*, 610–621. [CrossRef]
21. Rodgers, S.K.; Kirby, C.L.; Smith, R.J.; Horrow, M.M. Imaging after cesarean delivery: Acute and chronic complications. *Radiographics* **2012**, *32*, 1693–1712. [CrossRef]
22. Nair, A.D.; Manchanda, S.; Gamanagatti, S.; Kachhawa, G.; Bhatla, N. Post caesarean section complications conundrum: Role of imaging. *Br. J. Radiol.* **2022**, *95*, 20211344. [CrossRef]
23. Faul, F.; Erdfelder, E.; Lang, A.-G.; Buchner, A. G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* **2007**, *39*, 175–191. [CrossRef]
24. Hinz, B. The myofibroblast: Paradigm for a mechanically active cell. *J. Biomech.* **2010**, *43*, 146–155. [CrossRef]
25. Jor, J.W.Y.; Parker, M.D.; Taberner, A.J.; Nash, M.P.; Nielsen, P.M.F. Computational and experimental characterization of skin mechanics: Identifying current challenges and future directions. *WIREs Syst. Biol. Med.* **2013**, *5*, 539–556. [CrossRef]