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TOPICAL REVIEW

Pelvic Floor Muscle Electromyography in Natural Delivery: A Scoping Review

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ABSTRACT Vaginal delivery (VD) can induce neuromuscular changes in the pelvic floor muscles (PFMs), contributing to urinary and fecal incontinence. This scoping review maps and synthesizes the available evidence on the use of electromyography (EMG) to detect and characterize PFM alterations across the peri-partum and postpartum periods, with attention to study designs, EMG acquisition protocols, reported EMG markers associated with childbirth, and research gaps. We searched Scopus, Web of Science, IEEE Xplore, PubMed, CINAHL, and Embase in early May 2026 using database-adapted strings. English-language studies employing EMG in women assessed before, during, or after childbirth were included. Results were synthesized narratively. From 1846 identified records, 51 studies were included. Evidence was highly heterogeneous in populations, timing, electrode/probe configurations, and signal processing/normalization, limiting comparability. Accordingly, the evidence is summarized descriptively. Nonetheless, amplitude-based measures tended to indicate lower recorded amplitude after VD than after cesarean section (CS) and, in some studies, in parous postpartum women compared with nulliparous controls, with possible partial recovery over time in selected cohorts; however, findings were not fully consistent and were influenced by assessment timing and methodology. Invasive EMG studies reported motor unit action potential characteristics and fiber-density findings consistent with denervation/reinnervation and neuromuscular remodeling. Emerging multichannel high-density intravaginal/intrarectal EMG has been explored in research settings, offering improved spatial resolution, which may help to better capture localized dysfunction. Standardized methodologies are needed to enhance clinical translation.

INDEX TERMS Childbirth, electromyography (EMG), pelvic floor muscles (PFMs), scoping review.

I. INTRODUCTION

The pelvic floor (PF) consists of ligaments, fascial tissues and two main layers of muscles. The superficial one includes the bulbospongiosus (BS), ischiocavernosus (IC), superficial transverse perineal (ST) and the external anal sphincter (EAS) muscles. In contrast, the deeper layer includes the pubovaginal, the pubovisceral, puboperineal, iliococcygeal and puborectal muscles [1]. The role of the mentioned groups is to support the pelvic organs, maintain urinary and fecal continence, and contribute to sexual function [1].

The prevalence of PF disorders (PFDs) has been reported to reach 32% among females [2] and 16% among males [3] worldwide. Factors such as older age, menopause, obesity, connective tissue disorders, or physical activity are significant contributors [4]. However, traumatic events such as vaginal delivery (VD) are among the main causes of PFDs [5]. These conditions can negatively affect physical health, leading to urinary [6], [7] and fecal incontinence [8], with overt trauma and subtle neuromuscular impairments contributing to dysfunction [9], [10], [11], [12], [13], [14], [15].

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Furthermore they can also negatively impact the social life of an individual [16]. In the context of VD, lacerations of the perineum may occur and are known as perineal tears [17], [18]. Tears are classified into four grades (I° to IV°), with increasing grade depending on their severity [19]. Overall, they pose a serious clinical problem, occurring in up to 90 % of VDs regardless of classification, and are strongly associated with an increased risk of PFDs [20].

Perineal tears result from the stretching of tissues as the fetus passes through the birth canal [21], [22] and are more frequently observed in primiparous parturients [19], [23]. It has also been reported that the likelihood of spontaneous perineal tearing in a second delivery rose with the severity of perineal trauma sustained during the first birth [24].

Digital palpation is the most commonly used clinical method for assessing PF muscle contraction capacity [25], [26]. This requires active patient participation through voluntary contraction of the PFMs during the examination [25]. As a quantification metric, the Modified Oxford Scale is typically used [27], [28], [29], rating contractions on a scale from 0 (*no contraction*) to 5 (*strong contraction*) [30]. The scale is easy to implement, nevertheless, it has a few inherent limitations related to the subjective nature of the test, which can affect the inter-rater test reliability [8], [31].

The above justifies the need for reliable and subject independent approaches for accurate diagnosis and treatment monitoring of the PFDs [6]. Among such strategies are magnetic resonance imaging, transvaginal ultrasound, anal endosonography, perineometry, manometry, and electromyography (EMG) [6], [9], [31], [32]. There have been considerable applications for EMG recordings in recent years [6], [29], [32], [33]. Indeed, these are being used to analyze neurophysiological changes in PFMs contractions [32] and to directly assess the active tone of the PF [29]. In addition to its diagnostic role, EMG is also used to complement some treatments such as biofeedback [34], where muscle electrical activity is recorded, and feedback is provided through auditory or acoustic stimuli to promote motor learning [7], [35].

Although several studies have used EMG to assess PFMs function and potential injury, the evidence on childbirth-related EMG alterations remains dispersed and has not been comprehensively mapped. Therefore, this scoping review aims to identify, chart, and synthesize the available literature on EMG assessment of the PFM in relation to childbirth, describing the study characteristics, measurement protocols, and reported EMG markers of damage, and highlighting key knowledge gaps to guide future research.

In this review, we provide a concise overview of PF anatomy (Section I-A), a brief introduction to EMG (Section I-B), the research strategy employed in this review and our findings (Section III), and finally our conclusions, recommendations and future perspective in Section IV.

A. OVERVIEW OF PELVIC FLOOR ANATOMY

The superficial PFMs (EAS, BS, IC and ST muscles) are primarily involved in continence mechanisms and voluntary closure of the pelvic outlets. The EAS is a striated muscle encircling the anal canal and is innervated by branches of the pudendal nerve, making it especially vulnerable to stretch-related neuropathy during natural delivery [36], [37].

The deep layer mainly corresponds to the levator ani muscle (LAM) complex, composed of the puborectalis, pubococcygeus and iliococcygeus muscles. This muscular sling provides structural support to pelvic organs and plays a critical role in maintaining pelvic stability under increased intra-abdominal pressure [38]. Due to their depth, complex fiber orientation and partial overlap with surrounding structures, selective assessment of LAM activity using surface EMG (sEMG) remains technically challenging.

To facilitate comprehension, we refer the reader to see Fig. 1 where a multi-axis view of the PF anatomy is provided. From a neurophysiological standpoint, PFMs exhibit heterogeneous fiber composition and anisotropic architecture, with regional differences in innervation density and motor unit (MU)(i.e., the motor neuron and the muscle fibers it innervates) [39] distribution. These characteristics strongly influence EMG signal amplitude, spatial distribution and susceptibility to crosstalk. Understanding this anatomical and functional organization is therefore essential for interpreting EMG alterations associated with pregnancy, childbirth-related trauma and postpartum neuromuscular remodeling.

B. FUNDAMENTALS OF ELECTROMYOGRAPHY

From a physiological point of view, a muscle is composed of several MUs. EMG is an interference signal resulting from the asynchronous summation of multiple action potentials (MUAPs) [40], [41], each given by the summation of the action potentials of the muscle fibers constituting the MU [42].

To collect the EMG signal, electrodes that differ in dimension, materials and classes are used. The first class includes sensors (e.g., needle or wire electrodes) meant to penetrate the skin and reach the target(s) muscles of interest. The invasive electrodes are positioned adjacent to the fiber membranes, thus enabling the capture of selective information from the fibers located close to their tip [43]. The second-class electrodes include sensors meant to be placed on the individual's skin or into a natural orifice. The use of these electrodes allows the exploration of a large detection volume; thus, the resulting signal records the activity of multiple MUs [40], [41].

An additional distinction should be made regarding the density of the system adopted for EMG recording. Using high-density recording systems (i.e., exploiting multiple equidistant electrodes for data recording, usually placed in a linear array or a two-dimensional grid), makes it possible to extract monopolar from bipolar signals [44], investigate the EAS geometry [45], extract individual MUAPs [46],

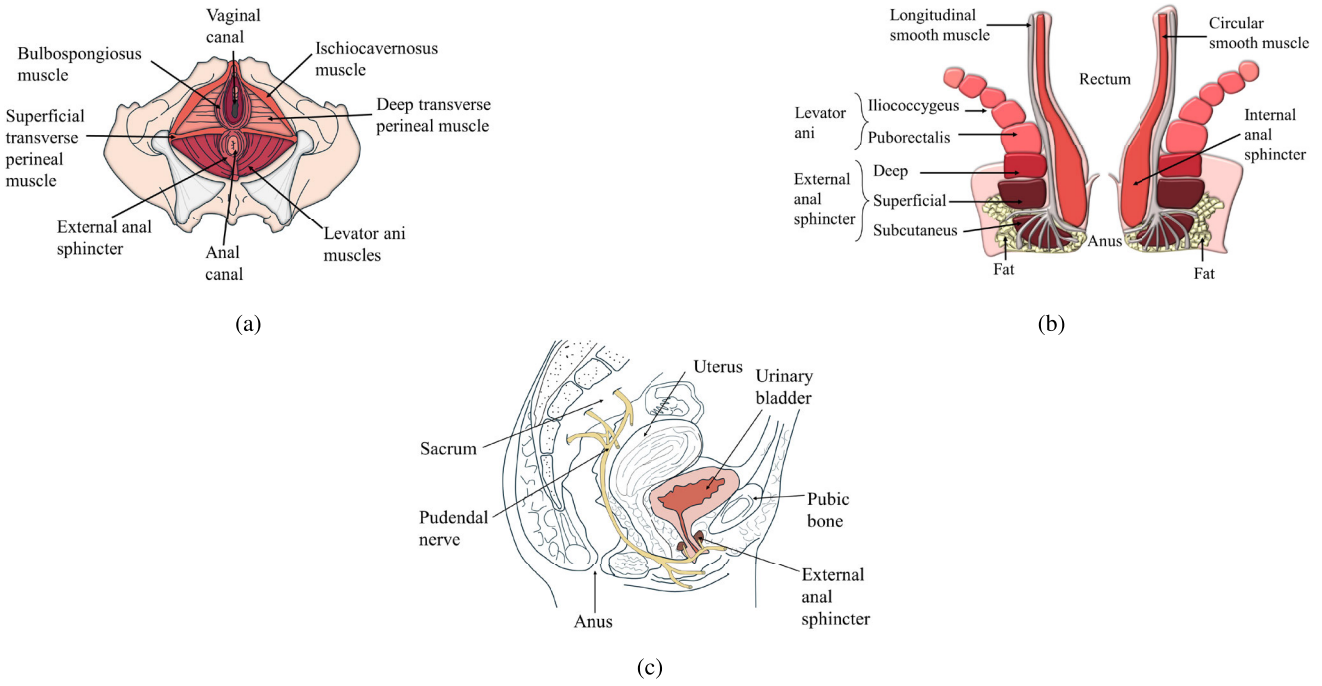


FIGURE 1. Pelvic floor anatomy illustrations. (a) Caudal view of the perineal muscles: perineal body, ischiocavernosus muscle, bulbospongiosus muscle, superficial transverse perineal muscle, and external anal sphincter. (b) Frontal view of the external and internal anal sphincters. Layers of the external sphincter (deep, superficial, subcutaneous), levator ani muscles (iliococcygeus, puborectalis), longitudinal smooth muscle, circular smooth muscle, with the latter forming the internal anal sphincter (IAS) near the anal canal, are represented. (c) Sagittal pelvic view showing the course of the pudendal nerve (yellow) from S2–S4 and its relationships with pelvic organs, highlighting its role in perineal and sphincter innervation.

[47], [48] from which important properties are obtained on MU anatomy [49], [50] and their control [51].

MUAPs can serve as markers of muscle structural and functional alterations. Reinnervation, resulting from nerve injury and perineal tears following childbirth [52], [53], can substantially modify MUAP characteristics. Reinnervated MUs typically exhibit increased amplitudes, more polyphasic waveforms, and prolonged durations [54].

II. METHODS

A. OBJECTIVES AND THEMATIC DOMAINS

This scoping review aimed to map the available evidence on the use of EMG to assess PFMs in relation to pregnancy and childbirth. Specifically, the review addressed the following research questions: (i) Which PFMs and anatomical targets have been investigated using EMG in women before, during, or after childbirth? (ii) How have cohorts been characterized in terms of pregnancy status, parity, delivery mode, obstetric exposures, and timing of assessment? (iii) Which EMG acquisition devices, electrode configurations, and recording setups have been used? (iv) Which activation strategies and testing protocols have been adopted to elicit PFMs activity? (v) Which EMG-derived features have been proposed or reported as indicators of PFMs damage related to VD?

The outcomes were pre-specified as follows: 1) muscles or anatomical targets investigated; 2) cohort characterization (participant features and assessment timepoint); 3) devices for acquisition (instrumentation and recording setup); 4) activation strategies (tasks/protocols used to activate PFMs during EMG recording); 5) EMG-derived markers reported in relation to pregnancy-, delivery-, or postpartum-related PF neuromuscular function or impairment.

B. RESEARCH STRATEGY

The literature search was performed at the beginning of May 2026 across six bibliographic databases: Scopus, Web of Science, IEEE Xplore, PubMed, Embase, and CINAHL via EBSCOhost. The search strategy was expanded to capture studies using EMG to assess PFMs in relation to pregnancy, childbirth, delivery mode, parity, perineal trauma, episiotomy, instrumental delivery, cesarean section (CS), and the postpartum period.

Search strings combined three main concepts: EMG-related terms, PFMs terms, and obstetric exposure terms. The full search strategy for each database is reported in the Supplementary Material. Searches were applied to all records indexed in each database from inception to the search date. A total of 1846 records were identified.

C. ELIGIBILITY CRITERIA

Full-text original studies were considered eligible if they were written in English and used EMG to assess PFMs in female participants before, during, or after pregnancy and childbirth. Although the primary focus of this review was EMG evidence related to VD, studies including CS-only cohorts, pregnancy-only assessments, or nulliparous/parous

comparator groups were retained when they provided contextual or comparative data useful for interpreting VD-related EMG findings and distinguishing VD effects from broader pregnancy-, childbirth-, or postpartum-related neuromuscular changes.

Studies were excluded if they were not original full-text articles, were conference abstracts only, were not written in English, did not report extractable EMG outcomes, or did not include a pregnancy-, childbirth-, parity-, or obstetric exposure-related context. Reviews, editorials, letters, and animal studies were excluded. Methodological studies without a relevant obstetric population were also excluded. Studies primarily focused on unrelated clinical conditions, such as spinal cord injury, neurological disease, diabetes, cancer, or non-obstetric PFDs, were excluded. Finally, studies evaluating drug effects, botulinum toxin, electrical stimulation, biofeedback treatment efficacy, sports, or virtual reality interventions were also excluded.

D. STUDY SELECTION PROCEDURE

The flowchart for study selection is illustrated in Fig. 2. The database search identified 1846 records, of which 1063 duplicates were removed using Rayyan [55]. The remaining 783 records were screened by title and abstract, and 78 studies were considered to potentially meet our pre-set inclusion criteria and were selected for full-text review. Of these, 77 studies were successfully retrieved and examined against the review inclusion/exclusion criteria.

Of these, 26 full-text reports were excluded for the following reasons: conference abstract only (n = 8), outcome not relevant to childbirth-related PF EMG assessment (n = 6), non-English language (n = 2), and non-extractable EMG outcome or data (n = 10). Overall, 51 studies were included in the final synthesis.

Title/abstract screening and full-text assessment were performed independently by two reviewers (CA, MR), who were blinded to each other's decisions. Any disagreements were resolved through discussion until a consensus was reached.

E. DATA EXTRACTION

Data extraction was performed independently by two reviewers (CA, MR), using an extraction form. Any disagreements were resolved through discussion until a consensus was reached. When consensus could not be achieved, a third reviewer (LM) was consulted. Extracted items included: (i) muscles/anatomical targets investigated and the EMG approach used; (ii) cohort characterization (participant features, sample size and evaluation timepoint relative to delivery); (iii) devices and acquisition setup; (iv) activation strategies and testing protocols; and (v) EMG-derived markers interpreted by the authors as indicators of childbirth-related PFM impairment/damage.

As a scoping review to capture the broad scope of evidence in the studied field, a formal risk-of-bias assessment of included studies was not performed [56]. A narrative synthesis was performed, and results were organized according to the pre-specified thematic domains.

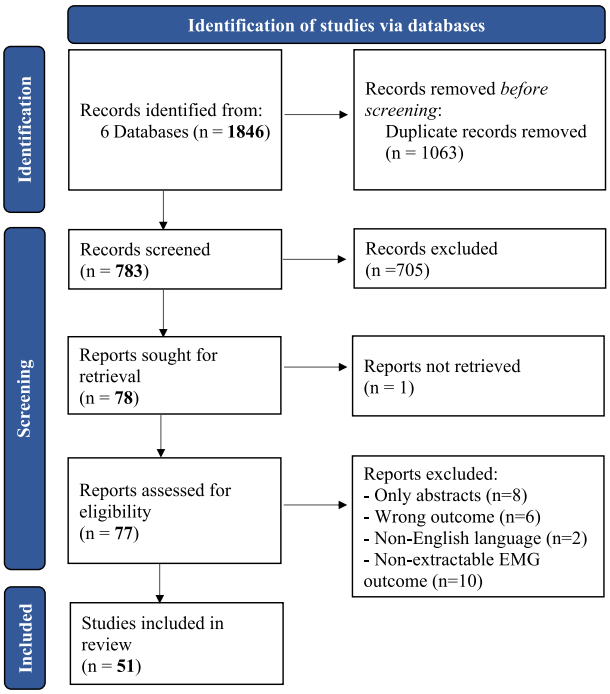


FIGURE 2. PRISMA flowchart for studies identification, screening and selection.

III. RESULTS

A. INVESTIGATED MUSCLES

In the context of childbirth-related PF damage assessed through EMG, the most studied muscle was the EAS (35.3%) [10], [12], [13], [14], [15], [52], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68]. Beyond the findings of the studies included in this review, the clinical relevance of the EAS is supported by its established role in continence and by its direct innervation by the pudendal nerve [69], which, due to cumulative stretching and compression during childbirth [53], can be injured. Obstetric anal sphincter injuries (OASIs) are reported to be highly prevalent during natural delivery [70], occurring in 2-19% of cases [71], and are strongly associated with postpartum fecal incontinence [72]. Investigations on the EAS are summarized in Table 1.

In the majority of selected articles (51%) (shown in Table 2 and Table 3), the activity of the PFMs was reported without specifying which muscles were actually recorded. In this review, we therefore refer to these studies as assessing global PFMs. Given that most of these studies used vaginal probes, the recorded signals are likely to include activity from muscles adjacent to the vaginal wall, particularly the pubococcygeus muscle [73], with possible

contributions from the puborectalis muscle [74] and other surrounding structures. Accordingly, these recordings should be interpreted as global vaginal PFM EMG activity rather than muscle-specific measurements, and later physiological interpretations based on these studies should be considered with caution.

Although less frequently examined, the LAMs (11.7%) [11], [75], [76], [77], [78], [79] also play a crucial role in postpartum PF function. The paucity of their representation in EMG-based research is likely a reflection of their anatomical complexity and depth, making direct assessment more challenging. Nevertheless, from a clinical perspective, LAMs integrity is considered relevant because trauma to these muscles has been associated with reduced PF strength and accompanying OASIs [70]. In this context, OASIs has been proposed as a marker of an underlying or occult LAM injury [80], thereby indicating that postpartum PF dysfunction involves both the sphincteric and supportive components of the musculature [81], [82]. Research specifically dedicated to the LAMs is presented in Table 4.

B. COHORTS CHARACTERIZATION

The selected articles encompassed heterogeneous cohorts of women assessed before, during, or after pregnancy and childbirth. For clarity, a brief explanation of terms commonly adopted in studies involving pregnancy and childbirth is provided here. Nulligravid refers to women who have never been pregnant, whereas primigravid refers to women during their first pregnancy [107]. Nulliparous refers to women who have never given birth [108], whereas parous refers to women who have given birth to at least one child [108]. Parous women are further classified as primiparous, indicating one previous delivery [76], [109], or multiparous, indicating more than one delivery [76].

Cohort designs varied substantially across the included studies. A common approach was to compare women with no previous pregnancy or delivery with women who had already delivered, using nulligravid or nulliparous participants as controls [11], [12], [14], [63], [75], [79], [89], [97], [100], [103], [104].

Additionally, some studies recorded EMG activity exclusively in pregnant women during the third trimester, without including any postpartum assessment [57], [99], [102], [104]. In contrast, pregnancy was used to provide baseline data for postpartum follow-up for longitudinal studies [13], [61], [62], [63], [66], [68], [76], [77], [78], [84], [89], [95], [98].

Overall, regardless of whether postpartum follow-up was included, the reviewed literature suggests that prepartum assessments are most commonly performed during the third trimester. Clinically, this timing appears meaningful, as PFM myoelectric activity has been reported to be reduced during the final stage of gestation [110], likely due to pregnancy-related physiological adaptations and fetal load-induced mechanical strain [111]. Moreover, the incidence of stress urinary incontinence (SUI) has been reported to increase during this period [112].

Several studies assessed women exclusively during the postpartum period, conducting postpartum follow-up evaluations without including prepartum measures within the same cohort, as reported in the *Cohort/timing* sections of Table 1, Table 2, Table 3, and Table 4. However, regardless of whether postpartum assessments were conducted as postpartum-only follow-ups or as part of longitudinal studies including pregnancy assessments, assessment timing varied considerably across studies. Evaluation points ranged from very early postpartum assessments at approximately 48-72 hours after delivery, to later evaluations at 4-6 weeks, 3 months, 6 months, and up to 12 months postpartum. This variability should be considered when interpreting the findings, particularly because some studies did not clearly specify the timing of postpartum assessment or included evaluation points that differed substantially across participants [12], [59], [67], [88], [92], [94].

In our interpretation, this heterogeneity is clinically relevant because postpartum recovery trajectories may depend on the location and severity of childbirth-related nerve or muscle injury [52], [53], [113]. This rationale is supported by peripheral nerve-regeneration processes described in the literature [114]. The pudendal nerve is reported to be vulnerable to stretching or compression during VD [52], [53], [113] and plays a major role in postpartum dysfunction [19]. Since the pudendal nerve arises from the sacral plexus (S2–S4) [115] and peripheral nerve regeneration has been estimated at approximately 1 mm/day [114], proximal injuries (e.g. at the ischial spine) may require three to six months for recovery [13], [116], [117], whereas recovery from more distal injuries affecting superficial branches, such as the inferior rectal or perineal nerves [115], could, in our interpretation, follow different trajectories depending on the distance to the target muscle and the extent of tissue damage.

Within the postpartum literature, studies specifically investigated obstetric exposures or childbirth-related trauma. These included delivery mode comparisons, such as VD versus CS [10], [62], [83], [86], [91], [93], cesarean timing [84], parity [11], [79], [88], [99], [102], episiotomy or perineal trauma [61], [66], [68], [94], [95], [98], birth weight [106], prolonged second stage of labor [79], and OASIS or childbirth-related anal sphincter rupture [58], [60], [63], [64]. Additionally, several studies enrolled postpartum symptomatic clinical cohorts, including women with SUI [9], [75], [92] or fecal/anal incontinence [15], [59], [65], [67].

Finally, one study assessed PFM activity during labor as part of simultaneous intrapartum recordings [90]. This approach may offer insights into PF activity during childbirth; however, its feasibility and scope of investigation are necessarily limited by the clinical complexity and sensitivity of the intrapartum setting.

TABLE 1. Summary of studies assessing the EAS using EMG. Studies are grouped by EMG modality as EAS recordings included needle/single-fiber EMG, low-density anal surface EMG, and high-density intra-anal sEMG.

Cohort / timing	Sensor	EMG features	Activation	Ref.
Concentric needle EMG and single-fiber EMG				
Nulliparous controls (n=28) vs primiparas after first VD (n=23); 12 weeks postpartum	Concentric needle	MUAP amplitude, duration, area, area/amplitude ratio, turns, phases and polyphasia	Relaxed EAS; light VC if needed; MVC/cough for recruitment	[14]
Primiparas after first VD, with/without anal incontinence (n=42); 24.7 ± 2.0 weeks after delivery	Concentric needle	MUAP parameters; interference-pattern turns/s, amplitude/turn, activity and envelope	Progressive voluntary contraction to MVC	[65]
Women with 3rd/4th-degree ASR 3-41 months postpartum (n=27); controls with no ASR (n=15)	SFEMG	EAS fiber density	NR	[58]
Women with FI after VD (37)	SFEMG / sphincter mapping	Fiber density; MUAP duration/amplitude and number	Rest; MVC	[67]
Parous women grouped by age and delivery mode (n=49)	Concentric needle	MUAP amplitude, duration, area, turns, phases and multiphase ratio	Mild contraction	[10]
Nulliparous (n=18) vs parous women (n=26); 1-55 years postpartum	Concentric needle	Multi-MUAP parameters; interference-pattern turn/amplitude analysis	Relaxation; voluntary/reflex activation; MVC/cough	[12]
FI after childbirth-related EAS division (n=20)	Needle / SFEMG	Sphincter mapping; fiber density	NR	[15]
Women assessed 48-72 h and 2 months postpartum (n=122); antenatal subgroup (n=51)*	SFEMG	Fiber density	Rectal balloon traction	[52]
Low-density anal surface EMG and EAS-related neurophysiology				
Nulliparous (n=16), parous controls 3-5 days and 3 months postpartum (n=24); ASR cohort 3-5 days,3,6 and 12 months postpartum (n=38)*	Anal sponge electrode	Maximum sEMG amplitude**	Rest; VCs	[63]
Women with FI (n=151); obstetric history recorded	Anal probe (3 electrodes)	sEMG amplitude**; anal-to-abdominal sEMG amplitude ratio**; normal/abnormal classification	Cough; VCs; push	[59]
ASR after childbirth (n=94); early and 3 months postpartum	Anal electrode	Maximum sEMG amplitude**	Rest; VCs	[64]
Primiparous (n=40), uncomplicated VD within 6 months postpartum (n=15), and OASIS 6-12 months postpartum (n=50)	Anal plug electrode	RMS peak sEMG amplitude; left-right amplitude symmetry index	MVC	[60]
Multichannel intra-anal surface EMG				
Nulliparous pregnant women (n=478)	Rectal probe (16 electrodes)	Amplitude envelopes and distributions; MUs and IZs distribution, MUs peak amplitude, CV, and width	Rest; MVC	[57]
Primiparas; pregnant (n=511), 28-34 weeks (n=511), and subgroup 6-8 weeks postpartum (n=331)*	Rectal probe (16 electrodes)	Amplitude envelopes and distributions; MUs and IZs distribution, IZs number	Rest; MVC	[66]
CS reference (n=1) and VD with episiotomy (n=4), 24 h before and 48h postpartum*	Rectal probe (16 electrodes)	ARV amplitude envelopes and distributions; MUs and IZs distribution	Rest; MVC	[68]
Nulliparous pregnant women (n=245); subgroup 6-8 weeks postpartum (n=167)*	Rectal probe (16 electrodes)	Mean ARV amplitude; asymmetry index	Rest; ramp-up; MVC; ramp-down	[61]
VD vs CS; pregnant (n=102), subgroup 6 weeks (n=80), and 1 year postpartum (n=62)*	Rectal probe (16 electrodes)	Mean ARV amplitude	MVC	[62]

Abbreviations and notes: ARV: average rectified value; ASR: anal sphincter rupture; CS: cesarean section; CV: conduction velocity; EAS: external anal sphincter; EMG: electromyography; FI: fecal incontinence; IZ: innervation zone; MU: motor unit; MUAP: motor unit action potential; MVC: maximal voluntary contraction; NR: not reported; OASIS: obstetric anal sphincter injuries; RMS: root mean square; sEMG: surface electromyography; SFEMG: single-fiber electromyography; VD: vaginal delivery. Numbers in parentheses in the Cohort/timing column indicate the number of participants in each cohort, when reported. *: Follow-up study. **: Estimation method not reported.

C. DEVICES FOR EMG ACQUISITION

The included articles reported different EMG acquisition approaches, including probes for natural orifices and invasive needle, single-fiber, or fine-wire electrodes.

Fig. 3 provides a graphical overview of the data collection systems employed in the selected studies. Because the acquisition strategy was closely related to the anatomical target investigated, in this representation, devices were represented according to the target muscle group.

1) INVASIVE ELECTRODES

Invasive needle, single-fiber, and fine-wire electrodes were mainly adopted in studies targeting the LAMs, where electrodes were inserted percutaneously to record from structures such as the pubococcygeus, puborectalis, or iliococcygeus muscles [11], [75], [76], [77], [78], [79]. They were also used in EAS-related studies to assess MU morphology, interference-pattern parameters, fiber density, or denervation/reinnervation features [10], [12], [13], [14], [15], [52], [58],

TABLE 2. Summary of studies assessing global PFM activity using vaginal or perineal EMG, part 1.

Cohort / timing	Sensor	EMG features	Activation	Ref.
Primiparous pregnant and 45 days postpartum (n=75); grouped by delivery mode*	Vaginal SEMG probe	RMS mean sEMG amplitude of 3 MVCs	MVCs (5s)	[83]
Postpartum CS (n=707) antepartum CS vs intrapartum CS; 42-60 days postpartum*	Vaginal sEMG probe	sEMG amplitude** as the median of the representative cohort	Glazer-type protocol	[84]
Primiparas after VD (n=3362); 42-60 days postpartum	Vaginal sEMG probe	Glazer-derived phase-specific sEMG parameters***	Glazer protocol	[85]
Primigravids after VD with episiotomy vs CS (n=260); 6 months postpartum	Vaginal sEMG probe and ECG electrodes on the perineum	RMS mean sEMG amplitude of the middle 5 s of the recorded wave at each stage	Glazer-type protocol	[86]
Postpartum; 40 days-6 months postpartum (n=21 302)	Vaginal sEMG probe	Glazer-derived phase-specific sEMG parameters***	Glazer protocol	[87]
Postpartum grouped by parity (n=971)	Vaginal sEMG probe	Glazer-derived phase-specific sEMG parameters***	Glazer protocol	[88]
Nulligravid (n=24); antepartum and postpartum with CS (n=13), with VD (n=89) grouped by perineal trauma; 6 weeks and 6 months postpartum*	Vaginal sEMG probe	sEMG peak** and 10-s endurance perineal muscle scores	Rest, MVCs	[89]
Intrapartum assessment (n=28)	Surface ECG electrodes on the perineum	sEMG total power, peak PDS, mean RMS, and burst duration	Labor-related contractions / intrapartum monitoring/ post-espulsion	[90]
Primiparas grouped by delivery mode (n=1259); 6-8 weeks postpartum	Vaginal sEMG probe	sEMG amplitude at rest**, mean sEMG amplitude** of 5 MVCs for fast contractions, mean sEMG amplitude** of 10 MVCs for fast contractions	Glazer-type protocol	[91]
Primiparas with postpartum symptomatic SUI (n=70 pairs); matched by delivery mode	Vaginal sEMG probe	Glazer-derived phase-specific sEMG parameters***	Glazer protocol	[92]
Primiparas (n=543) VD and CS; 6-8 weeks postpartum	Vaginal sEMG probe	Glazer-derived phase-specific sEMG parameters***	Glazer protocol	[93]
Antepartum (n=695) e postpartum (n=596) in a randomized episiotomy trial	Vaginal sEMG probe	Mean sEMG amplitude**	VCs	[94]
Antepartum and postpartum VD (n=595) and CS (n=106); 3 months postpartum*	Vaginal sEMG probe	Mean sEMG amplitude**	VCs	[95]

Abbreviations and notes: CS: cesarean section; ECG: electrocardiogram; EMG: electromyography; MVC: maximal voluntary contraction; PFM: pelvic floor muscle; PSD: power spectral density; RMS: root mean square; sEMG: surface electromyography; SUI: stress urinary incontinence; VC: voluntary contraction; VD: vaginal delivery. Numbers in parentheses in the Cohort/timing column indicate the number of participants in each cohort, when reported. *: Follow-up study. **: Estimation method not reported. ***For Glazer-derived phase-specific sEMG parameters, see [93].

[65], [67]. One additional study used concentric needle EMG to assess the striated urethral sphincter [118]. However, despite their selectivity, these solutions appear mainly in studies before 2010 [11], [12], [13], [14], [52], [58], [75], [76], [79], which we interpret as a shift toward less invasive devices.

2) SUPERFICIAL ELECTRODES

In this review, probes or surface systems were classified as low-density (LD) when they included fewer than 16 electrodes. LD systems were widely used and appeared in all studies investigating global PFMs (Tables 2 and 3). However, they were less frequent in EAS studies, where they included anal sponge electrodes or LD rectal probes [59], [60], [63], [64]. The most common LD configuration consisted of probes with two recording electrodes. Representative images of this type of probe are available in [102]. LD probes are usually preferred in vaginal examinations because their proximity to the vaginal walls allows a less invasive evaluation than needle or wire electrodes [33].

However, the pelvic region is characterized by high muscle density and multidirectional fiber orientation [119], [120], features that may reduce recording selectivity and increase the risk of crosstalk [121], [122], [123]. Hence, external surface electrodes are reported as critical [33], and although intravaginal and intra-rectal probes have been recommended for more stable and clinically feasible recordings than external surface electrodes alone [6], [124], their limited spatial resolution suggests that EMG amplitudes should be interpreted as global PFM activity rather than muscle-specific activity. These anatomical and methodological considerations suggest that non-invasive sEMG recordings in this region should be interpreted with caution. Consistently, the literature highlights that this issue is particularly relevant when using low-density probes with few and relatively large electrodes [29]. Such acquisition-related limitations may also have implications for the repeatability and reliability of sEMG recordings. The reliability of vaginal LD probes has been reported in nulliparous women [125], [126], [127]; however, reliability data in pregnant women remain limited, and postpartum evidence is limited to reports of moderate

TABLE 3. Summary of studies assessing global PFM activity using vaginal or perineal EMG, part 2.

Cohort / timing	Sensor	EMG features	Activation	Ref.
Postpartum grouped by age and parity (n=245); 42-60 days postpartum	Vaginal sEMG probe	Glazer-derived phase-specific sEMG parameters***	Glazer protocol	[96]
Nulliparous (n=10) vs primiparas 9-10 months after first VD (n=10)	Vaginal sEMG probe	Anterior and posterior ARV sEMG amplitude** during MVCs normalised by the ARV sEMG at rest **	Rest; MVCs	[97]
Primiparas after first VD with (n=200)/without (n=162) episiotomy; 6 weeks, 6, 12, and 24 months postpartum*	Vaginal sEMG probe	Glazer-derived phase-specific sEMG parameters***	Glazer protocol	[98]
Primigravids (n=19) vs secundigravidae (n=21) in the third trimester	Vaginal sEMG probe	RMS mean sEMG amplitude	MVCs (6s)	[99]
Nulliparous (n=12) and primiparas with grade II tears (n=9); 8-9 weeks postpartum	Vaginal sEMG probe	Resting sEMG amplitude**, MVC peak sEMG amplitude**	Rest; MVCs (4s)	[100]
Patients across female life-cycle groups (n=384), including pregnancy and postpartum groups	Vaginal sEMG probe	Mean RMS sEMG amplitude of 3 MVCs	MVCs (5s)	[101]
Pregnant in the third trimester; nulliparous (n=30) vs multiparous (n=30)	Vaginal sEMG probe	Mean, minimum, and maximum RMS sEMG amplitude	MVCs	[102]
Nulliparous (n=20) and primiparous after VD (n=20) or CS (n=20); 1-3 years postpartum	Vaginal sEMG probe	Maximum RMS sEMG amplitude normalised by the average of the RMS value of abdominal contraction sEMG amplitude	MVCs (5s)	[103]
Pregnant (n=15) and nonpregnant nulliparous (n=15)	Vaginal sEMG probe	Maximum RMS sEMG amplitude	Rest; MVCs (5)	[104]
Primiparas after delivery (n=52); 32-56 days postpartum	Vaginal sEMG probe and anal sEMG probe	sEMG amplitude**	Contract/relax tasks	[105]
Postpartum with SUI (n=241) and asymptomatic (n=1 139); 6-8 weeks postpartum	Vaginal sEMG probe	Resting, phasic, tonic and endurance sEMG amplitude**	Glazer-type protocol	[9]
Postpartum with SUI (n=509) and asymptomatic (n=2 520); 42 days postpartum	Vaginal sEMG probe	Glazer-derived phase-specific sEMG parameters***	Glazer protocol	[35]
Primiparas grouped by neonatal birth weight (n=200); 6-8 weeks and 1 year postpartum	Vaginal sEMG probe	Average or maximum device-derived sEMG amplitudes** depending on protocol phase	Glazer-type protocol	[106]

Abbreviations and notes: ARV: average rectified value; CS: cesarean section; EMG: electromyography; MVC: maximal voluntary contraction; PFM: pelvic floor muscle; sEMG: surface electromyography; SUI: stress urinary incontinence; VD: vaginal delivery. This table summarizes studies assessing global vaginal/perineal PFM activity rather than anatomically isolated external anal sphincter, levator ani, or urethral sphincter recordings. Numbers in parentheses in the Cohort/timing column indicate the number of participants in each cohort, when reported. *: Follow-up study. **: Estimation method not reported. ***For Glazer-derived phase-specific sEMG parameters, see [93].

intra-rater reliability in primiparous women with grade II perineal tears [100].

High-density (HD) probes were defined in this review as embedded systems with 16 or more electrodes. HD probes were used in studies targeting the EAS with multichannel intra-rectal probes [57], [61], [62], [66], [68]. An early example of this approach is the multichannel intra-rectal probe originally developed by Merletti and colleagues [49], which has since been refined through multiple design upgrades and adopted in multi-center studies to evaluate HD-EMG patterns before and after VD [128]. More reference images and technical details of this type of probe are available in Cescon et al. [57].

Compared with LD configurations, HD probes enable simultaneous recordings from multiple circumferential sites [129] and are reported to facilitate the detection of localized amplitude reductions, altered signal propagation, or recruitment imbalances, as the high electrode density and smaller electrode dimensions provide higher spatial resolution of muscle activity [130]. Methodological evidence suggests that HD intra-rectal probes may be particularly informative for spatially resolved EAS assessment [130], and among the included studies, these probes were used in research contexts involving obstetric injuries extending posteriorly to the anal sphincter complex, including medio-lateral episiotomy and obstetric anal sphincter injury [61], [62], [66], [68]. However, the available evidence does not yet support interpreting these applications as established clinical tools. Studies adopting HD probe technology were among the more recently published articles included in this review, suggesting that spatially resolved non-invasive EMG assessment is a possible emerging methodological direction.

To facilitate interpretation of HD versus LD recordings, we performed simulations of EAS EMG based on a cylindrical volume-conductor model [131]. Full simulation methods and results are reported in Supplementary Material S1,

TABLE 4. Summary of studies assessing the LAMs using EMG.

Cohort / timing	Sensor	EMG features	Activation	Ref.
Primigravids antenatal (n=82) and 2 months postpartum (n=75)*	Needle electrode in the pubococcygeus	MUAP amplitude, duration, and polyphasia	VCs	[13]
Nulliparous continent (n=10) vs parous with SUI (n=8)	Bilateral wire electrodes in the pubococcygeus	Tonic-phasic pattern; holding time; coordinated bilateral recruitment	Rest; VCs; cough; Valsalva; supine and standing positions	[75]
Primigravids (n=30) and multigravids (n=50) assessed before pregnancy, during pregnancy, and during the first 5 postpartum months*	Concentric needle EMG	MUAP amplitude	Rest; VCs; strain	[76]
Nulliparous (n=20); primipara (n=30) and multiparous (n=50) postpartum; stratified by normal vs prolonged second stage of labor	Concentric needle EMG	MUAP amplitude	Rest; strain	[79]
Nulliparous (n=20) and VD multiparous (n=60) postpartum, grouped by number of deliveries	Concentric needle EMG	MUAP amplitude	Rest; strain	[11]
Primigravid (n=58) assessed in third trimester, 6 weeks postpartum, and 6 months postpartum*	Concentric needle EMG at four levator sites: bilateral puborectalis and iliococcygeus	Turns/amplitude analysis; MUAP amplitude; turns/s; percentage of abnormal points outside the antepartum normal cloud	Rest; partial VCs; MVCs	[77]
Primigravid (n=58) assessed in third trimester, 6 weeks postpartum, and 6 months postpartum[a]*	Concentric needle quantitative EMG targeting puboviceralis and iliococcygeus	Interference-pattern analysis; denervation and reinnervation classification	Rest; moderate VCs; MVCs	[78]

Abbreviations and notes: EMG: electromyography; LA: levator ani; LAM: levator ani muscle; MVC: maximal voluntary contraction; MUAP: motor unit action potential; QEMG: quantitative electromyography; VC: voluntary contraction. *: Follow-up study. Numbers in parentheses in the Cohort/timing column indicate the number of participants in each cohort, when reported.
[a]South et al. [78] was considered a secondary analysis/companion publication of the Weidner et al. [77] cohort and was therefore interpreted as complementary rather than fully independent evidence.

showing that a 16-channel HD ring configuration preserves IZ identifiability (evidenced by flattened bipolar traces at the IZs and inversion of both polarity and propagation direction nearby), whereas LD configurations (4 channels or single bipolar) do not.

These differences in acquisition setup limit the direct comparability of EMG findings across studies. In particular, values obtained with vaginal LD probes, needle EMG, anal surface electrodes, and HD intra-rectal probes reflect different signal sources and different levels of spatial selectivity.

D. ACTIVATION STRATEGIES AND TESTING PROTOCOLS

1) VOLUNTARY ACTIVATION TASKS

Voluntary contractions (VCs) were the predominant activation strategy across the included studies. VCs include maximal voluntary contractions (MVCs), defined as the greatest consciously exerted effort [132], and submaximal contractions. In studies assessing global PFM activity, VCs were used in almost all cases, except one intrapartum study in which PFM EMG was recorded during labor-related contractions as part of simultaneous uterine, abdominal, and PF monitoring [90]. VCs were also widely used in EAS studies [10], [12], [14], [57], [59], [60], [61], [62], [63], [64], [65], [66]. In LAM studies, VC included MVCs, and straining-related contraction tasks [11], [13], [75], [76], [77], [78], [79].

From a methodological standpoint, verbal instructions, practice trials, or visual feedback may help improve task execution and reduce potential confounding factors, such as accessory muscle activation and crosstalk during VCs. When performing MVCs, as in other muscle groups, at least two or three contractions have been recommended [13], [75], [83], [97]. However, EMG amplitude does not increase proportionally with force [133], [134], [135], [136], [137] as the EMG-force relationship is non-linear and is affected by recruitment, firing rate, muscle architecture, and contraction intensity [137], [138], [139], [140], [141]. For this reason, when contraction levels are expressed relative to MVC, they should be interpreted as intended activation levels rather than direct measurements of mechanical force output. Additionally, for postpartum women, exerting reliable MVCs is reported to be difficult [142], [143] and is commonly associated with incorrect execution and co-activation of accessory muscles [142]. Although visual feedback helps reduce these errors [142], MVC reliability is still challenged by both physiological and methodological factors, including participant understanding, examiner instruction, and verbal cueing [144].

2) REFLEXIVE AND NON-VOLUNTARY ACTIVATION TASKS

Some of the included articles also reported the use of reflexive contractions as an activation strategy for PFMs, although with lower incidence compared to VCs; they are typically

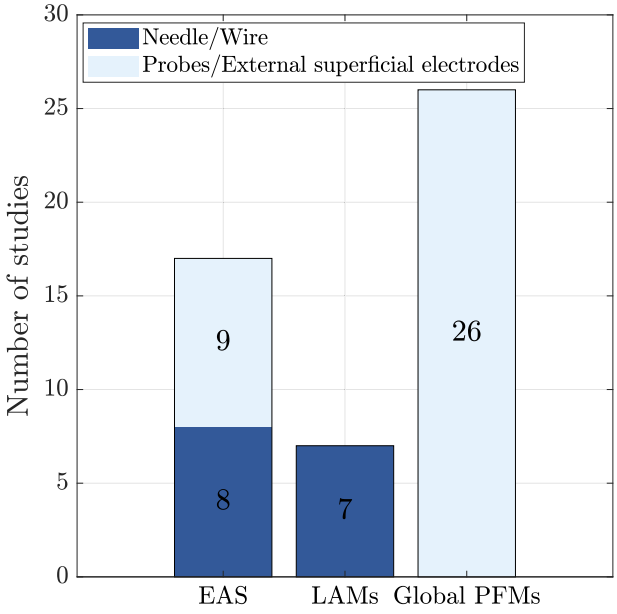


FIGURE 3. Number of studies using invasive electrodes (needle/wire) in dark blue and non-invasive solutions (vaginal or rectal probes) in light blue for the analyzed muscle groups: EAS, LAMs, and global PFMs. The numbers on the bars indicate the number of studies in each category. Stand-alone article about urethral sphincter [118] excluded from the illustration.

elicited through involuntary responses such as coughing and were used both in studies on the LAMs [75] and on the EAS [12], [14], [59], [145]. When reflexive contractions are adopted, it may be challenging to replicate consistent activation patterns. In the context of PFM assessment, this concern is supported by evidence showing that reflexive PFM activity can be highly variable and influenced by crosstalk from other muscles [146]. Push tasks and straining were also reported in a study assessing the EAS [59] and in a study evaluating the relation between the expelling forces during the pushing phase of the delivery and the sEMG [90]. Additionally, the included articles also reported the use of the Valsalva maneuver, defined as a forceful expiration against a closed glottis [147], as an activation strategy [75]. One EAS study also used rectal balloon traction to increase basal muscle activity during single-fiber EMG recording [52].

3) PROTOCOL HETEROGENEITY AND STRUCTURED ASSESSMENT

In line with these activation-related challenges, another key issue concerns the acquisition protocol. The included articles revealed substantial heterogeneity in EMG procedures, as many studies did not follow or fully report a structured protocol. Only a minority of studies adopted a clearly defined multi-phase protocol, with the Glazer protocol being the only reported structured option [35], [85], [88], [92], [93], [96], [98]. This protocol is based on VCs and comprises five sequential activities [148]:

- Pre-baseline rest (1 min).
- Phasic (“Flick”) contractions (5 repetitions): rapid contractions of the PF, each lasting 2 s with a 2-s rest between repetitions.
- Tonic contractions (5 × 10 s): sustained contractions of the PF, each held for 10 s, followed by 10 s of complete relaxation.
- Endurance contraction (60 s): contraction of the PF at a level sufficient to hold it for 60 s.
- Post-baseline rest (1 min).

By including different contraction and relaxation phases, this protocol provides comprehensive bioelectrical information beyond maximal contractions and relaxations [149]. Recent findings [150] indicate that, in healthy nulliparous women, multi-activity tasks and broader feature sets yield moderate-to-excellent reliability for time-domain and recruitment parameters, with frequency-domain fatigue measures showing higher reliability than those from the Glazer protocol. Nevertheless, the Glazer approach remains the most established and widely recognized structured protocol in the field.

Some studies adopted Glazer-type protocols rather than the exact original Glazer protocol [84], [91], [106]. These protocols generally retained the same overall structure, but differed in specific parameters such as contraction duration and rest interval between contractions. Therefore, although these studies can be broadly considered Glazer-type assessments, differences in task timing and phase definition may affect the extracted sEMG values and limit direct comparability across studies.

Because activation strategies differed in task type, contraction intensity, duration, number of repetitions, and rest intervals, EMG reported markers were interpreted according to the specific protocol adopted. Direct comparison across studies is therefore limited when activation tasks are not equivalent, even when the same anatomical target is assessed.

E. EMG MARKERS OF DAMAGE

The EMG features reported across clinical studies on PFMs in the included articles can be broadly classified into four main categories.

- **Global amplitude-related metrics**: Indices reflecting the overall signal magnitude.
- **MUAP characteristics**: Features describing the morphology of individual MUs.
- **Spatial markers**: Topographical features derived from IZ mapping.
- **Invasive indicators of neural remodeling**: Wire or needle-EMG metrics, such as fiber density.

The studies reporting the first two categories of EMG features, namely amplitude-related metrics and MUAP characteristics, are summarized in Table 5, Table 6, and Table 7, organized by anatomical target and cohort characteristics, to improve readability and facilitate comparison, as these were the most extensively reported feature categories.

1) AMPLITUDE-RELATED METRICS

Amplitude-related markers were the most frequently reported EMG-derived features across the included studies. They were used in studies assessing global PFM sEMG (see Table 2 and Table 3 in the *EMG Features* section) and EAS sEMG [59], [60], [62], [63], [64]. However, amplitude was extracted across the reviewed literature from different anatomical targets, recording systems, activation tasks, and signal-processing procedures; we therefore interpret amplitude-related findings as context-dependent descriptors of recorded myoelectric activity, rather than as a single, standardized marker of childbirth-related PFM damage. This context-dependent interpretation is further supported by signal-processing variability, as several studies reported absolute values, usually in μV, without specifying the estimator used, particularly in device-derived vaginal sEMG [9], [84], [89], [91], [94], [95], [97], [100], [105], [151] and low-density anal surface EMG studies [59], [63], [64].

The most recurrent pattern for studies focusing on global PFMs concerned the delivery mode.

Several studies reported lower superficial PFM sEMG amplitudes after VD than after CS, or higher rapid, tonic, endurance, or contraction-related amplitudes after CS than after VD [83], [86], [87], [91], [93]. Overall, these findings showed a broadly consistent direction of effect, although direct comparability is limited by differences in parity, postpartum timing, delivery-mode classification, and EMG protocols. Fang et al. provide large-cohort evidence supporting higher rapid, tonic, and endurance amplitudes after CS than after VD; however, their mixed-parity cohort and broad assessment window from 40 days to 6 months postpartum make it less directly comparable with primiparous-only early postpartum studies [87]. Botelho et al., Guo et al., and Jiang et al. assessed primiparous women in the early postpartum period (approximately 45 days to 6–8 weeks postpartum), and all support lower PFM activation or endurance after VD than after CS [83], [91], [93]. Danesh Shahraki et al. also reported better electrical activity and endurance after uncomplicated CS at 6 months postpartum, although the VD group consisted of women with episiotomy [86]. However, this evidence was not fully consistent. In one smaller study assessing women 1–3 years after first childbirth, normalized PFM sEMG amplitude during MVC did not differ significantly between nulliparous participants, participants after VD, and participants after CS [103]. We interpret this discrepancy as possibly reflecting differences in postpartum assessment timing, since early postpartum evaluations may capture transient delivery-related neuromuscular impairment, whereas later assessments may be influenced by recovery processes, tissue healing, and neuromuscular adaptation. Therefore, delivery mode may be associated with differences in recorded PFM activation, particularly in the early postpartum period, but amplitude alone should not be interpreted as a direct marker of persistent childbirth-related damage.

A second partially consistent pattern concerned comparisons between the nulliparous cohort and the post-VD cohort. One small study reported lower normalized vaginal PFM amplitude 9-10 months after first VD [99], whereas a larger life-cycle cohort similarly reported higher PFM sEMG amplitude in nulliparous than in post-VD participants [104]. These findings point in the same direction, but they are not directly comparable because they differ in sample size, postpartum timing, and amplitude processing.

Symptom-related findings were also reported in more than one cohort: postpartum cohorts with SUI or PF symptoms showed altered resting, phasic, tonic, or endurance-related sEMG values compared with asymptomatic cohorts [9], [35], [92]. This suggests that amplitude-based measures may be sensitive to postpartum clinical status, although the affected protocol phase differed across studies.

Other amplitude-related findings, including those concerning obstetric exposures, neonatal birth weight, episiotomy, perineal trauma, and isolated parity effects, were more heterogeneous or less directly comparable and are summarized in Table 5.

For EAS recordings, amplitude-related findings were more anatomically specific than global vaginal PFM recordings, but remained heterogeneous across clinical subgroups and EMG approaches. The only relatively consistent finding concerned childbirth-related EAS rupture. Two follow-up studies reported lower sEMG amplitude in the early postpartum period, with some indication of recovery over time [63], [64]. However, the two studies used different low-density recording setups. One study used an anal sponge electrode [63], whereas the other used a rectal probe [64], and neither reported the amplitude estimator. This limits direct comparison between their amplitude values. Other EAS amplitude findings, including those related to anal/fecal incontinence, EAS asymmetry, delivery mode, and longer-term recovery, were less consistent and are summarized in Table 6.

Taken together, these findings indicate that amplitude-related results were not fully consistent across anatomical targets and cohorts. Even when recurrent patterns were observed, they should be interpreted in light of methodological factors affecting amplitude estimation and normalization. Moreover, interpreting sEMG amplitude as an indicator of PF function depends partly on the normalization strategy used [152]. Normalization is intended to facilitate the comparison of signals from different electrode sites and the evaluation of changes over time [153], [154], as EMG amplitude is influenced by intrinsic factors such as fiber length, depth, diameter, and the amount of tissue between muscle and electrode [154], [155], and by extrinsic factors including muscle location, fiber orientation, and the geometry of the muscular region [154]. Body composition also contributes, since adipose layers attenuate the high-frequency components of the signal and may bias longitudinal analyses [153], [156], [157]. Acquisition-related

TABLE 5. Amplitude-related EMG findings in studies assessing global PFM activity. Findings are reported according to cohort/exposure.

Cohort or exposure	Amplitude-related findings
Pregnancy and parity	• Pregnant women showed lower vaginal PFM EMG amplitude than non-pregnant nulliparous women during resting or contraction tasks [104]. • Differences in PFM EMG amplitude during pregnancy were reported according to parity or gravidity, suggesting that pregnancy-related PFM activity may differ between nulliparous/primigravid and multiparous/secundigravid women [99], [102]. •The amplitude of tonic contraction was significantly lower in primiparous women than in secundiparous [88]. •Primiparous women showed significantly higher post-resting in respect to the multiparous counterpart [96]. •First VD was associated with lower vaginal PFM EMG contraction amplitude 9-10 months postpartum compared with nulliparous women [97]. •Nulliparous women showed higher PFM sEMG amplitude than women with previous VD [101].
Delivery mode and CS	• VD was associated with reduced postpartum PFM EMG activity compared with antepartum values, whereas CS showed no comparable reduction [83]. • CS was generally associated with higher rapid, tonic, endurance, or contraction-related sEMG amplitudes than VD, episiotomy, or forceps-assisted delivery [86], [87], [91], [93]. • No relevant differences in pre-resting, fast, sustained, or post-resting sEMG values were observed between antepartum and intrapartum CS groups [84]. • In women assessed 6 weeks postpartum [105] and 1-3 years [103] after first childbirth, normalized PFM sEMG amplitude during MVC did not differ significantly between VD, CS, and nulliparous groups.
Obstetric exposures	• Forceps-assisted delivery and prolonged second stage of labor were associated with increased risk of fast- and slow-twitch PFM strength decline [85]. • Higher neonatal birth weight was associated with lower PFM contraction-related amplitudes or poorer recovery of PFM sEMG parameters [87], [106].
Perineal trauma and episiotomy	• Episiotomy did not preserve perineal muscle function and was associated with poorer recovery or net loss of peak and endurance perineal muscle scores compared with other perineal outcomes [89], [95]. • Lower fast, tonic, or endurance contraction amplitudes were reported after episiotomy during postpartum follow-up [98]. • Primiparous women with grade II perineal tears showed lower resting and MVC peak sEMG activation than nulliparous women [100].
Postpartum SUI or symptoms	• Postpartum women with SUI or PF symptoms showed altered resting, fast/slow, or endurance-related sEMG values compared with asymptomatic women [9], [35], [92].

Abbreviations: EMG: electromyography; MVC: maximal voluntary contraction; PFM: pelvic floor muscle; RMS: root mean square; sEMG: surface electromyography; SUI: stress urinary incontinence.

TABLE 6. Amplitude-related EMG findings in studies assessing the EAS. Findings are reported according to cohort/exposure.

Cohort or exposure	Amplitude-related findings
EAS rupture, OASIS, or fecal incontinence	• In women with childbirth-related EAS rupture, resting anal sEMG was reduced in the first days after delivery compared with nulliparous controls, while squeeze sEMG was reduced at 3 and 6 months in women with EAS rupture compared with primiparous controls; no significant differences were observed at 12 months [63]. • In women with EAS rupture, anal sEMG amplitude increased from the first postpartum days to 3 months in both patients and controls [64]. • In women with childbirth-related third- or fourth-degree tears, higher left-right EAS amplitude asymmetry was associated with more severe incontinence symptoms, whereas this association was not evident in pregnant nulliparous women or after uncomplicated VD [60]. • In women with fecal incontinence, anal sEMG amplitude during cough/squeeze and the anal-to-abdominal amplitude ratio were used for normal/abnormal classification [59]. • In primiparas with anal incontinence symptoms, MUAP amplitude did not clearly differ between symptomatic and asymptomatic women [65]. • In women with fecal incontinence after VD, increased MUAP amplitude was interpreted as evidence of obstetric neurogenic injury [67].
VD, CS, and postpartum recovery	• Mean ARV amplitude during MVC showed a small decrease 6 weeks after VD, but returned to baseline by 1 year; no difference between VD and CS was observed at 1 year [62]. • The transient decrease in EAS amplitude after VD was not associated with changes in incontinence scores [62]. • In asymptomatic primiparas after first VD, MUAP amplitude, was larger than in nulliparous controls, suggesting neurogenic remodeling after uncomplicated VD [14]. • In women with remote uncomplicated obstetric history, quantitative EAS invasive EMG did not clearly support persistent EAS denervation after VD [12].

Abbreviations: ARV: average rectified value; CS: cesarean section; EAS: external anal sphincter; EMG: electromyography; MU: motor unit; MUAP/MUP: motor unit action potential/potential; MVC: maximal voluntary contraction; OASIS: obstetric anal sphincter injuries; sEMG: surface electromyography; VD: vaginal delivery.

aspects such as electrode placement, electrode size and shape, inter-electrode distance, spatial filtering, and crosstalk from adjacent muscles add further variability [155]. MVC-based normalization is particularly relevant in women with marked childbirth-related impairment who cannot produce a reliable MVC [142]. However, normalization was inconsistently reported across the included studies and, when described, was mainly based on peak MVC values [99], [158], [159], on the difference between MVC and resting activity [97], or on the difference between PFM MVC and MVC recorded on the abdominal muscles [103].

2) SPATIAL MARKERS AND INNERVATION-ZONE MAPPING

In addition to global amplitude-based EMG markers, the reviewed literature also reported spatially resolved EMG features related to PF neuromuscular organization. In EAS studies, spatial markers included amplitude distribution and asymmetry [61], MU decomposition, IZs number and spatial distribution [57], [66], [68]. All studies estimating or mapping IZs in the EAS relied on multichannel intra-anal surface EMG probes, as these have the features to potentially provide the reconstruction patterns of neuromuscular activation. HD-EMG studies reported asymmetric EAS innervation

TABLE 7. Amplitude-related EMG findings in studies assessing the LAMs. Findings are reported according to cohort/exposure.

Cohort or exposure	Amplitude-related findings
Pregnancy and postpartum	• LAMs EMG activity did not significantly differ from pre-pregnancy values during the first 8 weeks of pregnancy, then progressively increased until delivery during rest and squeeze tasks; during straining, EMG activity progressively decreased until delivery [76]. • Postpartum LAMs EMG activity was lowest during the first postpartum month and progressively recovered, reaching pre-pregnancy levels by approximately the fourth postpartum month [76]. • The reduction in LAMs EMG activity was more evident in multigravida than in primigravids women [76].
Parity and repeated deliveries	• LAMs EMG activity at rest and during contraction decreased progressively with increasing parity, following the pattern: nulliparous > multiparous > grand multiparous > great grand multiparous [11]. • LAMs EMG activity in grand multiparous and great grand multiparous women was interpreted as evidence that repeated deliveries may impair LAMs function [11].
Parous stress urinary incontinence	• Asymmetrical and uncoordinated pubococcygeus activation was observed in 4/8 parous stress-incontinent women [75].
Prolonged second stage of labor	• In multiparous women with normal delivery history, LAMs EMG activity at rest was similar to nulliparous controls, but activity during contraction was lower [79]. • In women with a history of prolonged second stage of labor, LAMs EMG activity was reduced both at rest and during contraction compared with nulliparous controls [79]. • with prolonged second stage also showed reduced LAMs activity at rest and during contraction, but the reduction was less pronounced than in multiparous with prolonged second stage [79].
Postpartum denervation/reinnervation	• Quantitative interference-pattern analysis showed EMG evidence of levator ani neuropathic injury in 24.1% of women at 6 weeks postpartum and 29.3% at 6 months postpartum [77]. • Women undergoing elective CS showed little or no levator ani EMG injury, whereas spontaneous VD, and CS after labor showed similar injury rates [77]. • In the secondary analysis, approximately 30% of women showed levator ani denervation/reinnervation patterns after first delivery; many women with abnormalities at 6 weeks recovered by 6 months, although persistent or newly detected abnormalities were also observed [78]. • Most abnormal turns:amplitude patterns were below the normal range, consistent with denervation rather than purely myopathic change [78].

Abbreviations: CS: cesarean section; EMG: electromyography; LAM: levator ani muscle; MVC: maximal voluntary contraction; PFM: pelvic floor muscle; VD: vaginal delivery.

patterns in both nulliparous and parous women, suggesting that innervation asymmetry may be partly physiological but may also be modified by childbirth-related trauma [57], [61]. Episiotomy and obstetric injury were reported to be associated with changes in IZ number or distribution, localized amplitude reductions, and altered asymmetry patterns in a large cohort study [66], with similar exploratory observations reported in a smaller study comparing one CS reference case with VD cases involving episiotomy [68]. These findings suggest that HD-EMG-derived spatial markers may provide complementary neuromuscular information to structural imaging for episiotomy planning, although their clinical interpretation remains limited by the small number of studies and by the current restriction of HD-EMG approaches to research settings.

3) INVASIVE EMG MARKERS: MUAP CHARACTERISTICS AND FIBER DENSITY

Other indicators of PF neuromuscular impairment included MUAP morphology and interference-pattern parameters, extracted from invasive EMG studies (see Table 1 and Table 4 in the *EMG features* section).

In EAS studies, longer or more complex MUAPs were reported in parous or postpartum women after VD [10], [14], whereas increased MUAP duration and amplitude with reduced recruitment were interpreted as signs of obstetric neurogenic injury in women with fecal incontinence after VD [67]. However, direct comparison across these studies is limited by differences or incomplete reporting of assessment timing as detailed in Table 1. EAS findings were also not uniform, as quantitative EMG did not clearly support persistent denervation in women with remote uncomplicated obstetric history [12]. However, the wide range of time since childbirth in this cohort, from 1 to 55 years, may have introduced substantial heterogeneity related to recovery, ageing, and long-term neuromuscular adaptation.

For LAM recordings, the most recurrent finding concerned postpartum denervation/reinnervation, reported in two related quantitative EMG analyses after first delivery [77], [78]. These studies reported LAM EMG abnormalities in approximately one quarter to one third of women during the early postpartum period and indicated that these abnormalities may change between 6 weeks and 6 months postpartum. Other LAM findings, including those related to pregnancy, increasing parity, prolonged second stage of labor, and parous SUI, were reported in isolated studies and are summarized in Table 7.

Evidence on the striated urethral sphincter was limited to a single included study. This study reported that turns/s, amplitude, and turns/amplitude ratio were already lower in primigravid women than in nulligravid controls before delivery and persisted postpartum with minimal recovery [118].

In addition to the previously described markers of neuromuscular injury, EAS fiber density detected with single-fiber needle electrodes was reported as a marker of neural remodeling [15], [52], [58], [67]. Increased EAS fiber density was observed in women after VD [52] with complete anal sphincter rupture after delivery [58] and with fecal incontinence after childbirth-related EAS division [15]. Fiber density may reflect collateral reinnervation after denervation, but it can only be assessed using invasive single-fiber needle EMG, limiting its applicability in routine clinical practice.

IV. FINAL REMARKS AND FUTURE PERSPECTIVES

In recent years, EMG has emerged as an increasingly potentially informative approach for investigating childbirth-related PFM impairment, and the literature reviewed in this study suggests that EMG may help capture meaningful postpartum neuromuscular changes; however, the strength of the current evidence is still limited by substantial heterogeneity across various domains. Differences in the anatomical targets investigated and the EMG approaches used to assess them, together with inconsistent cohort characterization (including participant features and widely variable evaluation timepoints), reduce comparability and hamper data pooling. Accordingly, the observed patterns emerging from the included studies should be interpreted as exploratory rather than conclusive, and should be considered hypothesis-generating until more standardized and longitudinal evidence becomes available. In addition, the frequent exclusion of women with severe perineal trauma leaves a clinically relevant subgroup understudied and limits generalizability. Moreover, variability in acquisition devices (sensor type, geometry, and recording setup) and in activation strategies used to elicit PFM activity further complicates interpretation, particularly because EMG remains susceptible to confounding factors such as crosstalk when large electrodes are used [160], [161], [162], reinforcing the need for improved recording solutions designs [33].

In this context, greater convergence on standardized activation procedures (e.g., structured protocols such as the Glazer protocol) and transparent reporting of feature extraction, estimation methods, artefact handling, and normalization may improve reproducibility and interpretability. This is especially important for amplitude-based markers, whose interpretation depends strongly on the selected normalization strategy and on the reliability of the reference contraction. Within this framework, longitudinal designs may be especially useful, as they allow EMG changes to be interpreted in relation to pre-delivery status, delivery-related exposures, and postpartum recovery. When combined with complementary imaging or diagnostic techniques, these designs may also help localize the site and extent of injury and determine when postpartum assessment is most informative in relation to tissue healing and neuromuscular reinnervation.

From a technical acquisition perspective, the reviewed literature highlights recurrent limitations that are particularly relevant for the more clinically feasible and increasingly adopted non-invasive sEMG approaches based on vaginal or rectal probes. Although these probes represent the most common solution in the studies included in this review, the comparability of low-density studies was limited by methodological issues, including amplitude estimation and normalization. Moreover, inconsistent probe positioning, variable electrode-tissue contact conditions, motion artefacts, and the absence of a mechanical reference for interpreting EMG amplitude further limit between-session comparability and physiological interpretation.

In addition to these methodological limitations, the reviewed literature also points to emerging technical developments in PF EMG, particularly recording HD approaches able to capture spatial information rather than only global signal amplitude. Mapping of IZs may provide topographical information on motor innervation pathways that cannot be derived from global amplitude alone [51], [129], [130] as also illustrated by the simulation results reported in Supplementary Material. This information is complementary to imaging modalities such as ultrasound [163], MRI [163], elastography [164], and thermography [165], which are widely used to assess structural or mechanical properties of the PF but cannot localize IZs. Accordingly, higher-density electrode configurations with optimized electrode size, inter-electrode distance, and circumferential/longitudinal coverage could improve spatial sampling, reduce crosstalk, and support the identification of localized activation patterns. Taken together, the HD-EMG findings suggest that spatial EAS features may capture both physiological asymmetry and childbirth-related modifications in neuromuscular organization. However, advanced information concerning single-MU activity relies on algorithms able to isolate single MUAPs from interference surface recordings [32], which may limit their practicality in routine clinical settings. Moreover, to our knowledge, clinically available probes do not generally implement HD detection. Indeed, their clinical interpretation remains preliminary, particularly for episiotomy-related applications, because validated thresholds and standardized acquisition protocols are still lacking.

Nevertheless, careful attention to practical acquisition issues is needed for both current LD probes and emerging HD approaches. Greater attention should be given to repeatable positioning across sessions, for example, through anatomical orientation markers, depth-control mechanisms, or shape features that help maintain a consistent position relative to the vaginal or anal wall. Because changes in electrode-tissue contact may alter signal amplitude independently of muscle activation, future probes could also incorporate contact-quality sensing, impedance monitoring, or inertial sensors to detect probe displacement, rotation, poor contact, and acquisition instability during recording. Finally, multimodal probes integrating force or pressure sensors could provide a mechanical reference for PFM contraction. This would help distinguish changes in myoelectric activation from changes in contractile output and could support more robust normalization when MVC performance is unreliable in postpartum women.

Addressing these gaps could support the advancement of EMG from an experimental tool to a reliable clinical instrument for the prevention, early detection, and management of childbirth-related PFDs, improving long-term outcomes and quality of life for women in the postpartum period. In the longer term, the systematic use of standardized EMG markers, particularly amplitude-related features and HD-EMG-derived innervation patterns, may contribute to

the development of evidence-based clinical guidelines. Such frameworks could support a more objective assessment of PFDs and help tailor rehabilitation strategies to achieve the ultimate aims of improving postnatal quality of life.

V. LIMITATIONS

This review has some limitations related to study retrieval, data extraction, synthesis, and interpretation of EMG markers. Although the search strategy covered six bibliographic databases and used database-adapted strings to capture EMG, PF, and childbirth-related terms, relevant studies may still have been missed because only English-language full-text original articles were included. In addition, one report could not be retrieved for full-text assessment.

Furthermore, included studies were highly heterogeneous in terms of populations, assessment timing, anatomical targets, electrode or probe configurations, activation protocols, signal processing and normalization. This heterogeneity prevented quantitative pooling and required a narrative synthesis.

Moreover, EMG-derived markers were interpreted according to the original studies and may be influenced by confounding factors such as crosstalk, probe positioning, electrode-tissue contact, normalization strategy, MVC reliability, and task execution. The limited use of common external reference standards, such as imaging, manometry, clinical grading, or longitudinal follow-up, further limits the direct link between EMG alterations and specific anatomical or functional outcomes.

Finally, findings related to high-density EMG and innervation zone mapping should be interpreted as exploratory. Although they may help describe spatial activation patterns and asymmetries with potential physiological relevance, these methods remain largely confined to research settings. Their clinical applicability is currently limited by the lack of commercially available PF probes with validated high-density detection, limited standardization of acquisition and analysis procedures, and the absence of established clinical thresholds.

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REFERENCES

[1] E. Gentilcore-Saulnier, L. McLean, C. Goldfinger, C. F. Pukall, and S. Chamberlain, "Pelvic floor muscle assessment outcomes in women with and without provoked vestibulodynia and the impact of a physical therapy program," *J. Sexual Med.*, vol. 7, no. 2, pp. 1003–1022, Feb. 2010.

[2] K. A. Kenne, L. Wendt, and J. Brooks Jackson, "Prevalence of pelvic floor disorders in adult women being seen in a primary care setting and associated risk factors," *Sci. Rep.*, vol. 12, no. 1, p. 9878, Jun. 2022.

[3] W. Grimes and M. Stratton, "Pelvic floor dysfunction," in *StatPearls [Internet]*. Treasure Island, FL, USA: StatPearls Publishing, 2023.

[4] S. Tim and A. I. Mazur-Bialy, "The most common functional disorders and factors affecting female pelvic floor," *Life*, vol. 11, no. 12, p. 1397, Dec. 2021.

[5] A. C. Diokno, "The cause of urinary incontinence," *Topics Geriatric Rehabil.*, vol. 3, no. 2, pp. 13–20, Jan. 1988.

[6] D. Michalik, U. Herman, and K. Stangel-Wojcikiewicz, "Quantitative tools to assess pelvic floor muscle function—Systematic review," *Ginekolog. Polska*, vol. 95, no. 9, pp. 718–728, Sep. 2024.

[7] Y. P. D. Kruif and E. E. van Wegen, "Pelvic floor muscle exercise therapy with myofeedback for women with stress urinary incontinence: A meta-analysis," *Physiotherapy*, vol. 82, no. 2, pp. 107–113, Feb. 1996.

[8] P. Enck, H. Hinninghofen, B. Wietek, and H. D. Becker, "Functional asymmetry of pelvic floor innervation and its role in the pathogenesis of fecal incontinence," *Digestion*, vol. 69, no. 2, pp. 102–111, 2004.

[9] X. Yang, L. Zhu, W. Li, X. Sun, Q. Huang, B. Tong, and Z. Xie, "Comparisons of electromyography and digital palpation measurement of pelvic floor muscle strength in postpartum women with stress urinary incontinence and asymptomatic parturients: A cross-sectional study," *Gynecolog. Obstetric Invest.*, vol. 84, no. 6, pp. 599–605, 2019.

[10] X. Li, C. Zhang, N. Dias, J. Liu, F. Hu, S. Yang, Y. Zhou, and Y. Zhang, "Effects of delivery mode and age on motor unit properties of the external anal sphincter in women," *Int. Urogynecol. J.*, vol. 30, no. 6, pp. 945–950, Mar. 2019.

[11] E. Kisli, M. Kisli, H. Agargun, F. Altinokyigit, M. Kamaci, E. Ozman, and C. Kotan, "Impaired function of the levator ani muscle in the grand multipara and great grand multipara," *Tohoku J. Experim. Med.*, vol. 210, no. 4, pp. 365–372, Dec. 2006.

[12] S. Podnar, A. Lukanovič, and D. B. Vodušek, "Anal sphincter electromyography after vaginal delivery: Neuropathic insufficiency or normal wear and tear?" *Neurourol. Urodynamics*, vol. 19, no. 3, pp. 249–257, Jan. 2000.

[13] R. E. Allen, G. L. Hosker, A. R. Smith, and D. W. Warrell, "Pelvic floor damage and childbirth: A neurophysiological study," *BJOG, Int. J. Obstetrics Gynaecol.*, vol. 97, no. 9, pp. 770–779, Sep. 1990.

[14] W. T. Gregory, J.-S. Lou, A. Stuyvesant, and A. L. Clark, "Quantitative electromyography of the anal sphincter after uncomplicated vaginal delivery," *Obstetrics Gynecol.*, vol. 104, no. 2, pp. 327–335, Aug. 2004.

[15] S. J. Snooks, M. M. Henry, and M. Swash, "Faecal incontinence due to external anal sphincter division in childbirth is associated with damage to the innervation of the pelvic floor musculature: A double pathology," *BJOG, Int. J. Obstetrics Gynaecol.*, vol. 92, no. 8, pp. 824–828, Aug. 1985.

[16] M. Leitner, H. Moser, J. Taeymans, A. Kuhn, and L. Radlinger, "Pelvic floor muscle displacement during voluntary and involuntary activation in continent and incontinent women: A systematic review," *Physiotherapy*, vol. 101, p. e857, May 2015.

[17] R. Man, V. H. Morton, and R. K. Morris, "Childbirth-related perineal trauma and its complications: Prevalence, risk factors and management," *Obstetrics, Gynaecol. Reproductive Med.*, vol. 34, no. 9, pp. 252–259, Sep. 2024.

[18] A. Akilimali, "The clinical characteristics of perineal tears: A study carried out on 14 pregnant women in a tertiary center: Case series," *Population Med.*, vol. 5, Apr. 2023, Art. no. 104432.

[19] E. Samuelsson, L. Ladfors, B. Lindblom, and H. Hagberg, "A prospective observational study on tears during vaginal delivery: Occurrences and risk factors," *Acta Obstetricia et Gynecologica Scandinavica*, vol. 81, no. 1, pp. 44–49, Jan. 2002.

[20] M. H. Jansson, K. Franzén, A. Hiyoshi, G. Tegerstedt, H. Dahlgren, and K. Nilsson, "Risk factors for perineal and vaginal tears in primiparous women—The prospective POPRACT-cohort study," *BMC Pregnancy Childbirth*, vol. 20, no. 1, pp. 1–14, Dec. 2020.

[21] R. Goh, D. Goh, and H. Ellepola, "Perineal tears—A review," *Austral. J. Gen. Pract.*, vol. 47, nos. 1–2, pp. 35–38, Feb. 2018.

[22] P. Głoćko, S. Janczak, A. Nowosielska-Ogórek, W. Patora, O. Wielgoszewska, M. Kozłowski, and A. Cymbaluk-Płoska, "Perspective on perinatal birth canal injuries: An analysis of risk factors, injury mechanisms, treatment methods, and patients' quality of life: A literature review," *J. Clin. Med.*, vol. 14, no. 10, p. 3583, May 2025.

[23] N. A. Okeahialam, A. H. Sultan, and R. Thakar, "The prevention of perineal trauma during vaginal birth," *Amer. J. Obstetrics Gynecol.*, vol. 230, no. 3, pp. S991–S1004, Mar. 2024.

[24] S. C. Martin, M. Labrecque, S. Marcoux, S. Bérubé, and J. Pinault, "The association between perineal trauma and spontaneous perineal tears," *J. Family Pract.*, vol. 50, no. 4, pp. 333–337, Apr. 2001.

[25] B. Messelink, T. Benson, B. Berghmans, K. Bø, J. Corcos, C. Fowler, J. Laycock, P. H.-C. Lim, R. van Lunsen, G. Lycklama á Nijeholt, J. Pemberton, A. Wang, A. Watier, and P. Van Kerrebroeck, "Standardization of terminology of pelvic floor muscle function and dysfunction: Report from the pelvic floor clinical assessment group of the international continence society," *Neurourol. Urodynamics*, vol. 24, no. 4, pp. 374–380, Jan. 2005.

[26] A. Devreese, F. Staes, W. De Weerdt, H. Feys, A. Van Assche, F. Penninckx, and R. Vereecken, "Clinical evaluation of pelvic floor muscle function in continent and incontinent women," *Neurourol. Urodynamics*, vol. 23, no. 3, pp. 190–197, Jan. 2004.

[27] L. Frazão, L. Couto, A. C. Peres, A. Marques, and A. Pássaro, "Assessment of female pelvic floor muscles: An integrative review," *Int. J. Women's Health*, vol. 17, pp. 2377–2393, Jul. 2025.

[28] A. Rai, N. Sharma, S. K. Jain, A. Lalwani, and S. Sharma, "Accuracy and reliability of different approaches for the assessment of pelvic floor muscle strength: A systematic review," *J. Pharmacy Bioallied Sci.*, vol. 15, no. 2, pp. S856–S861, Jul. 2023.

[29] R. Worman, R. E. Stafford, D. Cowley, and P. W. Hodges, "Methods used to investigate tone of pelvic floor muscles in pelvic health conditions: A systematic review," *Continence*, vol. 6, Jun. 2023, Art. no. 100593.

[30] I. Volløyhaug, S. Mørkved, Ø. Salvesen, and K. Å. Salvesen, "Assessment of pelvic floor muscle contraction with palpation, perineometry and transperineal ultrasound: A cross-sectional study," *Ultrasound Obstetrics Gynecol.*, vol. 47, no. 6, pp. 768–773, Jun. 2016.

[31] E. G. Deegan, L. Stothers, A. Kavanagh, and A. J. Macnab, "Quantification of pelvic floor muscle strength in female urinary incontinence: A systematic review and comparison of contemporary methodologies," *Neurourol. Urodynamics*, vol. 37, no. 1, pp. 33–45, Jan. 2018.

[32] Y. Peng, B. D. Miller, T. B. Boone, and Y. Zhang, "Modern theories of pelvic floor support: A topical review of modern studies on structural and functional pelvic floor support from medical imaging, computational modeling, and electromyographic perspectives," *Current Urol. Rep.*, vol. 19, no. 1, pp. 1–10, Jan. 2018.

[33] N. Keshwani and L. McLean, "State of the art review: Intravaginal probes for recording electromyography from the pelvic floor muscles," *Neurourol. Urodynamics*, vol. 34, no. 2, pp. 104–112, Feb. 2015.

[34] X. Wu, X. Zheng, X. Yi, P. Lai, and Y. Lan, "Electromyographic biofeedback for stress urinary incontinence or pelvic floor dysfunction in women: A systematic review and meta-analysis," *Adv. Therapy*, vol. 38, no. 8, pp. 4163–4177, Aug. 2021.

[35] H. Zhang, Y. Gou, J. Zhang, K. Liang, H. Li, and Y. Fang, "Analysis of pelvic floor electromyography in women screened 42 days postpartum: A cross-sectional study," *Medicine*, vol. 102, no. 21, May 2023, Art. no. e33851.

[36] C. Rubod, G. Giraudet, M. Cosson, O. Rastello, and P. Thiriet. *Le Périnée Féminin*. Accessed: May 2, 2026. [Online]. Available: https://anatomie3d.univ-lyon1.fr/ressources-peda/le-perinee-feminin/

[37] A. H. Sultan and R. Thakar, "Posterior compartment trauma and management of acute obstetric anal sphincter injuries," in *Pelvic Floor Disorders. A Multidisciplinary Textbook*, G. A. Santoro, A. P. Wieczorek, and A. H. Sultan, Eds., Cham, Switzerland: Springer, 2021, pp. 211–221.

[38] J. O. L. DeLancey, "Structural support of the urethra as it relates to stress urinary incontinence: The hammock hypothesis," *Amer. J. Obstetrics Gynecol.*, vol. 170, no. 5, pp. 1713–1723, May 1994.

[39] R. Merletti and S. Muceli, "Tutorial. Surface EMG detection in space and time: Best practices," *J. Electromyogr. Kinesiol.*, vol. 49, Dec. 2019, Art. no. 102363.

[40] L. Mesin, "Motor unit discharges from multi-kernel deconvolution of single channel surface electromyogram," *Electronics*, vol. 10, no. 16, p. 2022, Aug. 2021.

[41] L. Mesin, "Separation of interference surface electromyogram into propagating and non-propagating components," *Biomed. Signal Process. Control*, vol. 52, pp. 238–247, May 2019.

[42] P. Zhou and W. Z. Rymer, "MUAP number estimates in surface EMG: Template-matching methods and their performance boundaries," *Ann. Biomed. Eng.*, vol. 32, no. 7, pp. 1007–1015, Jul. 2004.

[43] D. I. Rubin, "Needle electromyography: Basic concepts," in *Handbook Clinical Neurology*, vol. 160, K. H. Levin and P. Chauvel, Eds., Amsterdam, The Netherlands: Elsevier, Jan. 2019, pp. 243–256.

[44] L. Mesin, "Estimation of monopolar signals from sphincter muscles and removal of common mode interference," *Biomed. Signal Process. Control*, vol. 4, no. 1, pp. 37–48, Jan. 2009.

[45] C. Cescon, L. Mesin, M. Nowakowski, and R. Merletti, "Geometry assessment of anal sphincter muscle based on monopolar multichannel surface EMG signals," *J. Electromyogr. Kinesiol.*, vol. 21, no. 2, pp. 394–401, Apr. 2011.

[46] C. Chen, D. Li, and M. Xia, "A motor unit action potential-based method for surface electromyography decomposition," *J. NeuroEng. Rehabil.*, vol. 22, no. 1, p. 60, Mar. 2025.

[47] G. Valli, P. Ritsche, A. Casolo, F. Negro, and G. D. Vito, "Tutorial: Analysis of central and peripheral motor unit properties from decomposed high-density surface EMG signals with openhdemg," *J. Electromyogr. Kinesiol.*, vol. 74, Feb. 2023, Art. no. 102850.

[48] A. Grison, I. Mendez Guerra, A. K. Clarke, S. Muceli, J. Ibáñez, and D. Farina, "Unlocking the full potential of high-density surface EMG: Novel non-invasive high-yield motor unit decomposition," *J. Physiol.*, vol. 603, no. 8, pp. 2281–2300, Apr. 2025.

[49] R. Merletti, A. Bottin, C. Cescon, D. Farina, M. Gazzoni, S. Martina, L. Mesin, M. Pozzo, A. Rainoldi, and P. Enck, "Multichannel surface EMG for the non-invasive assessment of the anal sphincter muscle," *Digestion*, vol. 69, no. 2, pp. 112–122, 2004.

[50] L. Mesin, M. Gazzoni, and R. Merletti, "Automatic localisation of innervation zones: A simulation study of the external anal sphincter," *J. Electromyogr. Kinesiol.*, vol. 19, no. 6, pp. e413–e421, Dec. 2009.

[51] Y. Peng, J. He, R. Khavari, T. B. Boone, and Y. Zhang, "Functional mapping of the pelvic floor and sphincter muscles from high-density surface EMG recordings," *Int. Urogynecol. J.*, vol. 27, no. 11, pp. 1689–1696, Nov. 2016.

[52] S. J. Snooks, M. Swash, M. M. Henry, and M. Setchell, "Risk factors in childbirth causing damage to the pelvic floor innervation," *Int. J. Colorectal Disease*, vol. 1, no. 1, pp. 20–24, Jan. 1986.

[53] M. Fitzpatrick and C. O. Herlihy, "The effects of labour and delivery on the pelvic floor," *Best Pract. Res. Clin. Obstetrics Gynaecol.*, vol. 15, no. 1, pp. 63–79, Feb. 2001.

[54] J. V. Trontelj, J. Jabre, and M. Mihelin, "Needle and wire detection techniques," in *Electromyography: Physiology, Engineering, and Non-invasive Applications*. Hoboken, NJ, USA: Wiley, 2004, pp. 27–46.

[55] M. Ouzzani, H. Hammady, Z. Fedorowicz, and A. Elmagarmid, "Rayyan—A web and mobile app for systematic reviews," *Systematic Rev.*, vol. 5, no. 1, p. 210, Dec. 2016.

[56] F. Campbell, A. C. Tricco, Z. Munn, D. Pollock, A. Saran, A. Sutton, H. White, and H. Khalil, "Mapping reviews, scoping reviews, and evidence and gap maps (EGMs): The same but different—The 'big pictur,' review family," *Systematic Rev.*, vol. 12, no. 1, p. 45, Mar. 2023.

[57] C. Cescon, E. E. Raimondi, V. Začesta, K. Drusany-Starič, K. Martsidis, and R. Merletti, "Characterization of the motor units of the external anal sphincter in pregnant women with multichannel surface EMG," *Int. Urogynecol. J.*, vol. 25, no. 8, pp. 1097–1103, Aug. 2014.

[58] A. Goffeng, B. Andersch, M. Andersson, I. Berndtsson, L. Hulten, and T. Öresland, "Objective methods cannot predict anal incontinence after primary repair of extensive anal tears," *Acta Obstetricia et Gynecologica Scandinavica*, vol. 77, no. 4, pp. 439–443, Jan. 1998.

[59] J. L. Swartz, A. Zifan, L. J. Tuttle, G. Sheean, R. M. Tam, and R. K. Mittal, "Fecal incontinence patients categorized based on anal pressure and electromyography: Anal sphincter damage and clinical symptoms," *Neurogastroenterol. Motility*, vol. 36, no. 7, p. 14810, Jul. 2024.

[60] B. M. Wietek, H. Hinninghofen, E. C. Jehle, P. Enck, and H. B. Franz, "Asymmetric sphincter innervation is associated with fecal incontinence after anal sphincter trauma during childbirth," *Neurourol. Urodynamics*, vol. 26, no. 1, pp. 134–139, Jan. 2007.

[61] V. Začesta, D. Rezeberga, H. Plaudis, K. Drusany-Staric, and C. Cescon, "Could the correct side of mediolateral episiotomy be determined according to anal sphincter EMG?" *Int. Urogynecol. J.*, vol. 29, no. 10, pp. 1501–1507, Feb. 2018.

[62] V. Začesta, L. Rācene, C. Cescon, H. Plaudis, and D. Rezeberga, "Sphincter muscle activity before and after delivery: Does it depend on the type of birth?" *J. Obstetrics Gynaecology Res.*, vol. 47, no. 2, pp. 705–712, Dec. 2020.

[63] M. Sørensen, T. Tetzschner, O. Ø. Rasmussen, J. Bjarnesen, and J. Christiansen, "Sphincter rupture in childbirth," *J. Brit. Surg.*, vol. 80, no. 3, pp. 392–394, Mar. 1993.

[64] T. Tetzschner, M. Sorensen, O. O. Rasmussen, G. Lose, and J. Christiansen, "Pudendal nerve damage increases the risk of fecal incontinence in women with anal sphincter rupture after childbirth," *Acta Obstetricia et Gynecolog. Scandinavica*, vol. 74, no. 6, pp. 434–440, Jun. 1995.

[65] W. T. Gregory, J.-S. Lou, K. Simmons, and A. L. Clark, "Quantitative anal sphincter electromyography in primiparous women with anal incontinence," *Amer. J. Obstetrics Gynecol.*, vol. 198, no. 5, pp. 550.e1–550.e6, May 2008.

[66] C. Cescon, D. Riva, V. Začesta, K. Drusany-Starič, K. Martsidis, O. Protsepko, K. Baessler, and R. Merletti, "Effect of vaginal delivery on the external anal sphincter muscle innervation pattern evaluated by multichannel surface EMG: Results of the multicentre study TASI-2," *Int. Urogynecol. J.*, vol. 25, no. 11, pp. 1491–1499, Nov. 2014.

[67] P. P. M. Jacobs, M. Scheuer, J. H. C. Kuijpers, and M. H. Vingerhoets, "Obstetric fecal incontinence: Role of pelvic floor denervation and results of delayed sphincter repair," *Diseases Colon Rectum*, vol. 33, no. 6, pp. 494–497, 1990.

[68] K. D. Starič, G. Norčič, G. Campo, and R. E. C. Distefano, "Episiotomy and innervation zones of the external anal sphincter: A case series investigating the impact on neurological patterns," *J. Electromyogr. Kinesiol.*, vol. 80, Feb. 2025, Art. no. 102970.

[69] H. H. Chang, U. Lee, T. Vu, V. Pikov, J. H. Nieto, K. L. Christe, and L. A. Havton, "EMG characteristics of the external anal sphincter guarding reflex and effects of a unilateral ventral root avulsion injury in rhesus macaques (*Macaca mulatta*)," *J. Neurophysiol.*, vol. 120, no. 6, pp. 2710–2718, Dec. 2018.

[70] I. Volløyhaug, A. Taithongchai, I. Van Gruting, A. Sultan, and R. Thakar, "Levator ani muscle morphology and function in women with obstetric anal sphincter injury," *Ultrasound Obstetrics Gynecol.*, vol. 53, no. 3, pp. 410–416, Mar. 2019.

[71] D. E. Fenner, B. Genberg, P. Brahma, L. Marek, and J. O. L. DeLancey, "Fecal and urinary incontinence after vaginal delivery with anal sphincter disruption in an obstetrics unit in the United States," *Amer. J. Obstetrics Gynecol.*, vol. 189, no. 6, pp. 1543–1549, Dec. 2003.

[72] D. Borello-France, K. L. Burgio, H. E. Richter, H. M. Zyczynski, M. P. FitzGerald, W. E. Whitehead, P. Fine, I. Nygaard, V. L. Handa, A. G. Visco, A. M. Weber, and M. B. Brown, "Fecal and urinary incontinence in primiparous women," *Obstetrics gynecol.*, vol. 108, no. 4, pp. 863–872, Oct. 2006.

[73] M. Roch, N. Gaudreault, M.-P. Cyr, G. Venne, N. J. Bureau, and M. Morin, "The female pelvic floor fascia anatomy: A systematic search and review," *Life*, vol. 11, no. 9, p. 900, Aug. 2021.

[74] V. Raizada and R. K. Mittal, "Pelvic floor anatomy and applied physiology," *Gastroenterology Clinics North Amer.*, vol. 37, no. 3, pp. 493–509, Sep. 2008.

[75] F. M. Deindl, D. B. Vodusek, U. Hesse, and B. Schüssler, "Pelvic floor activity patterns: Comparison of nulliparous continent and parous urinary stress incontinent women. A kinesiological EMG study," *Brit. J. Urol.*, vol. 73, no. 4, pp. 413–417, Apr. 1994.

[76] A. Shafik and O. El-Sibai, "Levator ani muscle activity in pregnancy and the postpartum period: A myoelectric study," *Clin. Experim. Obstetrics Gynecology*, vol. 27, no. 2, pp. 129–132, 2000.

[77] A. Weidner, M. Jamison, V. Branham, M. South, K. Borawski, and A. Romero, "Neuropathic injury to the levator ani occurs in 1 in 4 primiparous women," *Amer. J. Obstetrics Gynecol.*, vol. 195, no. 6, pp. 1851–1856, Dec. 2006.

[78] M. M. T. South, S. S. Stinnett, D. B. Sanders, and A. C. Weidner, "Levator ani denervation and reinnervation 6 months after childbirth," *Amer. J. Obstetrics Gynecol.*, vol. 200, no. 5, pp. 519.e1–519.e7, May 2009.

[79] A. Shafik and O. El-Sibai, "Study of the levator ani muscle in the multipara: Role of levator dysfunction in defecation disorders," *J. Obstetrics Gynaecol.*, vol. 22, no. 2, pp. 187–192, Jan. 2002.

[80] K. L. Shek, K. Green, J. Hall, R. Guzman-Rojas, and H. P. Dietz, "Perineal and vaginal tears are clinical markers for occult levator ani trauma: A retrospective observational study," *Ultrasound Obstetrics Gynecol.*, vol. 47, no. 2, pp. 224–227, Feb. 2016.

[81] N. Schwertner-Tiepelmann, R. Thakar, A. H. Sultan, and R. Tunn, "Obstetric levator ani muscle injuries: Current status," *Ultrasound Obstetrics & Gynecol.*, vol. 39, no. 4, pp. 372–383, Apr. 2011.

[82] S. Perrin and S. Billecocq, "[Impact of obstetric lesions of the levator ani on anal continence]," *Progres En Urologie : J. De l'Association Francaise d'Urologie et de la Societe Francaise D'urologie*, vol. 32, no. 17, pp. 1519–1530, Dec. 2022.

[83] S. Botelho, C. Riccetto, V. Herrmann, L. C. Pereira, C. Amorim, and P. Palma, "Impact of delivery mode on electromyographic activity of pelvic floor: Comparative prospective study," *Neurourol. Urodynamics*, vol. 29, no. 7, pp. 1258–1261, Sep. 2010.

[84] Y. Chen, C. Xu, Q. Saiding, X. Chi, L. Chu, X. Wang, and X. Chen, "Association of cesarean delivery timing with pelvic floor muscle function and urine incontinence: A propensity score-matched study," *Smart Med.*, vol. 1, no. 1, Dec. 2022, Art. no. e20220018.

[85] X. Chi, S. Yu, K. Zhu, Y. Chen, Y. Chu, and X. Chen, "Influence of different obstetric factors on early postpartum pelvic floor function in primiparas after vaginal delivery," *Int. J. Women's Health*, vol. 15, pp. 81–90, Jan. 2023.

[86] A. D. Shahraki, M. Hajhashemi, M. Movahedi, and F. Abbasi, "Correlation between delivery type and pelvic floor dysfunction: A case-control study," *Adv. Biomed. Res.*, vol. 14, no. 1, Apr. 2025 Art. no. 37.

[87] J. Fang, J. Ye, Q. Huang, Y. Lin, Y. Weng, M. Wang, Y. Chen, Y. Lu, and R. Zhang, "Risk factors of pelvic floor muscle strength in South Chinese women: A retrospective study," *BMC Pregnancy Childbirth*, vol. 22, no. 1, p. 624, Aug. 2022.

[88] J. Fang, R. Zhang, S. Lin, B. Lai, Y. Chen, Y. Lu, M. Wang, Y. Lin, Y. Weng, J. Lin, and J. Shen, "Impact of parity on pelvic floor morphology and function: A retrospective study," *Medicine*, vol. 102, no. 45, 2023, Art. no. e35738.

[89] N. Fleming, E. R. Newton, and J. Roberts, "Changes in postpartum perineal muscle function in women with and without episiotomies," *J. Midwifery Women's Health*, vol. 48, no. 1, pp. 53–59, Jan. 2003.

[90] K. M. Gray, L. Murphy, M. Chauhan, L. McCann, R. Gerkin, R. M. Starikov, and R. Garfield, "Simultaneous measurement of electrical activity of uterine, abdominal, and pelvic floor muscles during the second and third stages of labor," *Amer. J. Obstetrics Gynecol. MFM*, vol. 2, no. 4, Nov. 2020, Art. no. 100171.

[91] K.-M. Guo, L. He, Y. Feng, L. Huang, A. N. Morse, and H. Liu, "Surface electromyography of the pelvic floor at 6–8 weeks following delivery: A comparison of different modes of delivery," *Int. Urogynecol. J.*, vol. 33, no. 6, pp. 1511–1520, Jun. 2021.

[92] Y. Hongliang, L. Pengfei, J. Cuiping, H. Jieqian, P. Ling, and S. Yumin, "Pelvic floor function and morphological abnormalities in primiparas with postpartum symptomatic stress urinary incontinence based on the type of delivery: A 1:1 matched case–control study," *Int. Urogynecol. J.*, vol. 33, no. 2, pp. 245–251, Feb. 2022.

[93] J. Jiang, C. Li, H.-Y. Liu, and Z.-Y. Zhu, "Relationship between abnormal pelvic floor electromyography and obstetric factors in postpartum women: A cross-sectional study," *BMC Women's Health*, vol. 24, no. 1, p. 239, Apr. 2024.

[94] M. Klein, R. Gauthier, S. H. Jorgensen, J. M. Robbins, J. Kaczorowski, B. Johnson, M.-M. Corriveau, R. Westreich, K. Waghorn, and M. M. Gelfand, "Does episiotomy prevent perineal trauma and pelvic floor relaxation?" *Jordemodern*, vol. 106, no. 10, pp. 375–377, Nov. 1993.

[95] M. C. Klein, R. J. Gauthier, J. M. Robbins, J. Kaczorowski, S. H. Jorgensen, E. D. Franco, B. Johnson, K. Waghorn, M. M. Gelfand, M. S. Guralnick, G. W. Luskey, and A. K. Joshi, "Relationship of episiotomy to perineal trauma and morbidity, sexual dysfunction, and pelvic floor relaxation," *Amer. J. Obstetrics Gynecol.*, vol. 171, no. 3, pp. 591–598, Sep. 1994.

[96] Z. Mao, D. Hao, Q. Gao, Y. Meng, M. Zhou, and L. Zhang, "Effects of age and parity on pelvic floor dysfunction and recovery in the early postpartum period: A retrospective cohort study," *Brit. J. Hospital Med.*, vol. 86, no. 7, pp. 1–24, Jul. 2025.

[97] K. Marshall, D. M. Walsh, and G. D. Baxter, "The effect of a first vaginal delivery on the integrity of the pelvic floor musculature," *Clin. Rehabil.*, vol. 16, no. 7, pp. 795–799, Nov. 2002.

[98] L. Min, D. Xudong, L. Qiubo, L. Pingping, L. Yuhan, Z. Guifang, G. Tianzi, F. Qing, Y. Chunxue, and L. Yaxin, "Two year follow-up and comparison of pelvic floor muscle electromyography after first vaginal delivery with and without episiotomy and its correlation with urinary incontinence: A prospective cohort study," *Acta Obstetricia et Gynecolog. Scandinavica*, vol. 102, no. 2, pp. 200–208, Feb. 2023.

[99] A. S. Moccellin, M. T. Rett, and P. Driusso, "Electromyographic activity of the pelvic floor muscles in the third trimester: Comparison between primigravidae and secundigravidae," *Clin. Experim. Obstetrics Gynecol.*, vol. 43, no. 4, pp. 565–568, 2016.

[100] P. Mota, A. Costa, D. Santos, S. Santo, J. G. Barros, and K. Bø, "Pelvic floor muscle function after grade II tears—Surface electromyography test–retest and differences between nulliparous and primiparous," *Neurourol. Urodynamics*, vol. 42, no. 5, pp. 1162–1168, Jun. 2023.

[101] L. C. Pereira, S. Botelho, J. Marques, D. B. Adami, F. K. Alves, P. Palma, and C. Riccetto, "Electromyographic pelvic floor activity: Is there impact during the female life cycle?" *Neurourol. Urodynamics*, vol. 35, no. 2, pp. 230–234, Feb. 2016.

[102] C. D. Petricelli, A. P. M. Resende, J. Elito Júnior, E. Araujo Júnior, S. M. Alexandre, M. R. D. Zanetti, and M. U. Nakamura, "Distensibility and strength of the pelvic floor muscles of women in the third trimester of pregnancy," *BioMed Res. Int.*, vol. 2014, pp. 1–6, Apr. 2014.

[103] I. Pimentel-Soares, A. C. S. Beleza, M. D. S. Corrêa, M. V. Batistão, and P. Driusso, "Long-term effect of first childbirth on pelvic floor muscle function: Cross-sectional study," *Clin. Experim. Obstetrics Gynecol.*, vol. 46, no. 4, pp. 630–634, 2019.

[104] A. P. M. Resende, C. D. Petricelli, B. T. Bernardes, S. M. Alexandre, M. U. Nakamura, and M. R. D. Zanetti, "Electromyographic evaluation of pelvic floor muscles in pregnant and nonpregnant women," *Int. Urogynecol. J.*, vol. 23, no. 8, pp. 1041–1045, Aug. 2012.

[105] J. Thorp, L. Jones, W. Bowes, and W. Droegemueller, "Electromyography with acrylic plug surface electrodes after delivery," *Amer. J. Perinatol.*, vol. 12, no. 2, pp. 125–128, Mar. 2008.

[106] Y. Zhou, D. Wu, Q. Zhu, and L. Ling, "The influence of neonatal birth weight on postpartum pelvic floor function in primiparas," *Medicine*, vol. 105, no. 9, 2026, Art. no. e47723.

[107] K. Okunade, H. Okunola, L. Oyeneyin, and F. Habeeb-Adeyemi, "Cross-sectional study on the obstetric performance of primigravidae in a teaching hospital in Lagos, Nigeria," *Nigerian Med. J.*, vol. 57, no. 5, pp. 303–306, 2016.

[108] H. Maraj and S. Kumari, "No clarity on the definition of parity: A survey accessing interpretation of the word parity amongst obstetricians and midwives and a literature review," *Eur. J. Obstetrics Gynecol. Reproductive Biol.*, vol. 263, pp. 15–19, Aug. 2021.

[109] L. Viktrup, G. Rortveit, and G. Lose, "Does the impact of subsequent incontinence risk factors depend on continence status during the first pregnancy or the postpartum period 12 years before? A cohort study in 232 primiparous women," *Amer. J. Obstetrics Gynecol.*, vol. 199, no. 1, pp. 73.e1–73.e4, Jul. 2008.

[110] E. C. S. Furtado, Y. S. D. Azevedo, D. D. R. Galhardo, I. P. C. Miranda, M. E. C. Oliveira, P. F. M. das Neves, L. B. Monte, E. F. Carneiro Nunes, E. A. G. Ferreira, B. Callegari, G. D. S. Souza, and J. S. De Melo-Neto, "Influence of gestational age on pelvic floor muscle activity, plantar contact, and functional mobility in high-risk pregnant women: A cross-sectional study," *Sensors*, vol. 24, no. 14, p. 4615, Jul. 2024.

[111] K. K. Whitcome, L. J. Shapiro, and D. E. Lieberman, "Fetal load and the evolution of lumbar lordosis in bipedal hominins," *Nature*, vol. 450, no. 7172, pp. 1075–1078, Dec. 2007.

[112] C. Sun, H. Yang, K. Li, and P. He, "Pelvic floor structural changes during the first singleton pregnancy and the risk factors of stress urinary incontinence," *BMC Pregnancy Childbirth*, vol. 25, no. 1, p. 552, May 2025.

[113] A. H. Sultan, M. A. Kamm, and C. N. Hudson, "Pudendal nerve damage during labour: Prospective study before and after childbirth," *BJOG: Int. J. Obstetrics Gynaecol.*, vol. 101, no. 1, pp. 22–28, Jan. 1994.

[114] E. Gutmann, "Histology of degeneration and regeneration," in *Electrodiagnosis and electromyography*. New Haven, CT, USA: Licht Press, 1961, pp. 113–133.

[115] J. Zapletal, O. Nanka, M. J. Halaska, K. Maxova, L. Hajkova Hympanova, L. Krofta, and L. Rob, "Anatomy of the pudendal nerve in clinically important areas: A pictorial essay and narrative review," *Surgical Radiologic Anatomy*, vol. 46, no. 2, pp. 211–222, Jan. 2024.

[116] S. Snooks, P. Barnes, and M. Swash, "Damage to the innervation of the voluntary anal and periurethral sphincter musculature in incontinence: An electrophysiological study," *J. Neurol., Neurosurgery, Psychiatry*, vol. 47, pp. 1269–1273, Jan. 1985.

[117] T. Tetzschner, M. Sørensen, G. Lose, and J. Christiansen, "Pudendal nerve recovery after a non-instrumented vaginal delivery," *Int. Urogynecol. J. Pelvic Floor Dysfunction*, vol. 7, no. 2, pp. 102–104, Mar. 1996.

[118] A. C. Weidner, M. M. T. South, D. B. Sanders, and S. S. Stinnett, "Change in urethral sphincter neuromuscular function during pregnancy persists after delivery," *Amer. J. Obstetrics Gynecol.*, vol. 201, no. 5, pp. 529.e1–529.e6, Nov. 2009.

[119] F. M. Zijta, M. M. E. Lakeman, M. Froeling, M. P. van der Paardt, C. S. V. Borstlap, S. Bipat, A. D. Montauban van Swijndregt, G. J. Strijkers, J. P. Roovers, A. J. Nederveen, and J. Stoker, "Evaluation of the female pelvic floor in pelvic organ prolapse using 3.0-Tesla diffusion tensor imaging and fibre tractography," *Eur. Radiol.*, vol. 22, no. 12, pp. 2806–2813, Dec. 2012.

[120] S. Muro and K. Akita, "Pelvic floor and perineal muscles: A dynamic coordination between skeletal and smooth muscles on pelvic floor stabilization," *Anatomical Sci. Int.*, vol. 98, no. 3, pp. 407–425, Jul. 2023.

[121] L. Mesin, "Crosstalk in surface electromyogram: Literature review and some insights," *Phys. Eng. Sci. Med.*, vol. 43, no. 2, pp. 481–492, Jun. 2020.

[122] M. Raggi, G. Boccia, and L. Mesin, "Reduction of crosstalk in the electromyogram: Experimental validation of the optimal spatio-temporal filter," *IEEE Access*, vol. 11, pp. 112075–112084, 2023.

[123] D. Farina, R. Merletti, and D. F. Stegeman, "Biophysics of the generation of EMG signals," in *Electromyography: Physiology, Engineering, and Noninvasive Applications*, R. Merletti and P. A. Parker, Eds., Hoboken, NJ, USA: Wiley, 2004, pp. 81–105.

[124] N. Flury, I. Koenig, and L. Radlinger, "Crosstalk considerations in studies evaluating pelvic floor muscles using surface electromyography in women: A scoping review," *Arch. Gynecol. Obstetrics*, vol. 295, no. 4, pp. 799–809, Apr. 2017.

[125] H. H. Grape, Å. Dedering, and A. F. Jonasson, "Retest reliability of surface electromyography on the pelvic floor muscles," *Neurourol. Urodynamics*, vol. 28, no. 5, pp. 395–399, Jun. 2009.

[126] R. Scharschmidt, S. Derlien, T. Siebert, M. Herbsleb, and N. Stutzig, "Intraday and interday reliability of pelvic floor muscles electromyography in continent woman," *Neurourol. Urodynamics*, vol. 39, no. 1, pp. 271–278, Jan. 2020.

[127] C. C. Auchincloss and L. McLean, "The reliability of surface EMG recorded from the pelvic floor muscles," *J. Neurosci. Methods*, vol. 182, no. 1, pp. 85–96, Aug. 2009.

[128] N. Paskaranandavadivel, C. Varghese, J. Lara, S. Ramachandran, L. Cheng, A. Holobar, A. Gharibans, I. Bissett, R. Collinson, C. Stinear, and G. O'Grady, "A novel high-density electromyography probe for evaluating anorectal neurophysiology: Design, human feasibility study, and validation with trans-sacral magnetic stimulation," *Ann. Biomed. Eng.*, vol. 49, no. 1, pp. 502–514, Jan. 2021.

[129] P. Enck, H. Hinninghofen, R. Merletti, and F. Azpiroz, "The external anal sphincter and the role of surface electromyography," *Neurogastroenterol. Motility*, vol. 17, no. s1, pp. 60–67, Jun. 2005.

[130] N. Dias, X. Li, C. Zhang, and Y. Zhang, "Innervation asymmetry of the external anal sphincter in aging characterized from high-density intrarectal surface EMG recordings," *Neurourol. Urodynamics*, vol. 37, no. 8, pp. 2544–2550, Nov. 2018.

[131] D. Farina, L. Mesin, S. Martina, and R. Merletti, "A surface EMG generation model with multilayer cylindrical description of the volume conductor," *IEEE Trans. Biomed. Eng.*, vol. 51, no. 3, pp. 415–426, Mar. 2004.

[132] D. Meldrum, E. Cahalane, R. Conroy, D. Fitzgerald, and O. Hardiman, "Maximum voluntary isometric contraction: Reference values and clinical application," *Amyotrophic Lateral Sclerosis*, vol. 8, no. 1, pp. 47–55, Jan. 2007.

[133] A. C. Guimaraes, W. Herzog, M. Hulliger, Y. T. Zhang, and S. Day, "Effects of muscle length on the emg–force relationship of the cat soleus muscle studied using non-periodic stimulation of ventral root filaments," *J. Experim. Biol.*, vol. 193, no. 1, pp. 49–64, Aug. 1994.

[134] P. Madeleine, P. Bajaj, K. Søgaard, and L. Arendt-Nielsen, "Mechanomyography and electromyography force relationships during concentric, isometric and eccentric contractions," *J. Electromyogr. Kinesiol.*, vol. 11, no. 2, pp. 113–121, Apr. 2001.

[135] J. H. Lawrence and C. J. De Luca, "Myoelectric signal versus force relationship in different human muscles," *J. Appl. Physiol.*, vol. 54, no. 6, pp. 1653–1659, Jun. 1983.

[136] M. Solomonow, R. V. Baratta, and R. D'Ambrosia, "EMG-force relations of a single skeletal muscle acting across a joint: Dependence on joint angle," *J. Electromyogr. Kinesiol.*, vol. 1, no. 1, pp. 58–67, Jan. 1991.

[137] H. Kuriki, L. Takahashi, E. Mello, F. Azevedo, R. N. Filho, and N. Alves, "The relationship between electromyography and muscle force," in *EMG Methods for Evaluating Muscle and Nerve Function*, M. Schwartz, Ed., London, U.K.: IntechOpen, Jan. 2012.

[138] M. Bilodeau, S. Schindler-Ivens, D. M. Williams, R. Chandran, and S. S. Sharma, "EMG frequency content changes with increasing force and during fatigue in the quadriceps femoris muscle of men and women," *J. Electromyogr. Kinesiol.*, vol. 13, no. 1, pp. 83–92, Feb. 2003.

[139] B. Gerdle, K. Henriksson-Larsén, R. Lorentzon, and M.-L. Wretling, "Dependence of the mean power frequency of the electromyogram on muscle force and fibre type," *Acta Physiologica Scandinavica*, vol. 142, no. 4, pp. 457–465, Aug. 1991.

[140] W. Herzog, J. Sokolosky, Y. T. Zhang, and A. C. S. Guimarães, "EMG-force relation in dynamically contracting cat plantaris muscle," *J. Electromyogr. Kinesiol.*, vol. 8, no. 3, pp. 147–155, Jun. 1998.

[141] T. Moritani, S. Muramatsu, and M. Muro, "Activity of motor units during concentric and eccentric contractions," *Amer. J. Phys. Med. Rehabil.*, vol. 66, no. 6, pp. 338–350, Dec. 1988.

[142] H. Neels, S. De Wachter, J.-J. Wyndaele, T. Van Aggelpoel, and A. Vermandel, "Common errors made in attempt to contract the pelvic floor muscles in women early after delivery: A prospective observational study," *Eur. J. Obstetrics Gynecol. Reproductive Biol.*, vol. 220, pp. 113–117, Jan. 2018.

[143] I. Koenig, H. Luginbuehl, and L. Radlinger, "Reliability of pelvic floor muscle electromyography tested on healthy women and women with pelvic floor muscle dysfunction," *Ann. Phys. Rehabil. Med.*, vol. 60, no. 6, pp. 382–386, Nov. 2017.

[144] R. Aljuraifani, R. E. Stafford, L. M. Hall, and P. W. Hodges, "Activity of deep and superficial pelvic floor muscles in women in response to different verbal instructions: A preliminary investigation using a novel electromyography electrode," *J. Sexual Med.*, vol. 16, no. 5, pp. 673–679, May 2019.

[145] U. M. Peschers, A. Gingelmaier, K. Jundt, B. Leib, and T. Dimpfl, "Evaluation of pelvic floor muscle strength using four different techniques," *Int. Urogynecol. J. Pelvic Floor Dysfunction*, vol. 12, no. 1, pp. 27–30, Feb. 2001.

[146] H. Luginbuehl, J.-P. Baeyens, A. Kuhn, R. Christen, B. Oberli, P. Eichelberger, and L. Radlinger, "Pelvic floor muscle reflex activity during coughing—An exploratory and reliability study," *Ann. Phys. Rehabil. Med.*, vol. 59, nos. 5–6, pp. 302–307, Dec. 2016.

[147] V. J. Derbes and A. Kerr, "Valsalva's maneuver and weber's experiment," *New England J. Med.*, vol. 253, no. 19, pp. 822–823, Nov. 1955.

[148] C. R. Hacad and H. I. Glazer, "The glazer intrapelvic surface electromyography (SEMG) protocol in a case of male urinary incontinence and a case of female hypoactive sexual desire disorder," *Biofeedback*, vol. 40, no. 2, pp. 80–95, Jun. 2012.

[149] H. I. Glazer, L. J. Romanzi, and M. Polaneczky, "Pelvic floor muscle surface electromyography. Reliability and clinical predictive validity," *J. Reproductive Med.*, vol. 44, no. 9, pp. 779–782, Oct. 1999.

[150] Ł. Oleksy, A. Mika, I. Sulowska-Daszyk, E. Rosłoniec, R. Kielnar, and A. Stolarczyk, "The reliability of pelvic floor muscle bioelectrical activity (sEMG) assessment using a multi-activity measurement protocol in young women," *Int. J. Environ. Res. Public Health*, vol. 18, no. 2, p. 765, Jan. 2021.

[151] P. Zhou and W. Z. Rymer, "Factors governing the form of the relation between muscle force and the EMG: A simulation study," *J. Neurophysiol.*, vol. 92, no. 5, pp. 2878–2886, Nov. 2004.

[152] V. S. Pereira-Baldon, A. B. de Oliveira, J. F. Padilha, A. M. Degani, M. A. Avila, and P. Driusso, "Reliability of different electromyographic normalization methods for pelvic floor muscles assessment," *Neurourol. Urodynamics*, vol. 39, no. 4, pp. 1145–1151, Apr. 2020.

[153] G. J. Lehman and S. M. McGill, "The importance of normalization in the interpretation of surface electromyography: A proof of principle," *J. Manipulative Physiolog. Therapeutics*, vol. 22, no. 7, pp. 444–446, Sep. 1999.

[154] G. L. Soderberg and L. M. Knutson, "A guide for use and interpretation of kinesiologic electromyographic data," *Phys. Therapy*, vol. 80, no. 5, pp. 485–498, May 2000.

[155] R. Merletti, M. Knaflitz, and C. J. De Luca, "Myoelectric manifestations of fatigue in voluntary and electrically elicited contractions," *J. Appl. Physiol.*, vol. 69, no. 5, pp. 1810–1820, Nov. 1990.

[156] D. Farina and A. Rainoldi, "Compensation of the effect of sub-cutaneous tissue layers on surface EMG: A simulation study," *Med. Eng. Phys.*, vol. 21, no. 6, pp. 487–497, Jul. 1999.

[157] M. M. Lowery, N. S. Stoykov, A. Taflove, and T. A. Kuiken, "A multiple-layer finite-element model of the surface EMG signal," *IEEE Trans. Biomed. Eng.*, vol. 49, no. 5, pp. 446–454, May 2002.

[158] C. Ballmer, P. Eichelberger, M. Leitner, H. Moser, H. Luginbuehl, A. Kuhn, and L. Radlinger, "Electromyography of pelvic floor muscles with true differential versus faux differential electrode configuration," *Int. Urogynecol. J.*, vol. 31, no. 10, pp. 2051–2059, Oct. 2020.

[159] M. Leitner, H. Moser, P. Eichelberger, A. Kuhn, and L. Radlinger, "Pelvic floor muscle activity during fast voluntary contractions in continent and incontinent women," *Neurourol. Urodynamics*, vol. 38, no. 2, pp. 625–631, Feb. 2019.

[160] K. Bø and M. Sherburn, "Evaluation of female pelvic-floor muscle function and strength," *Phys. Therapy*, vol. 85, no. 3, pp. 269–282, Mar. 2005.

[161] P. Neumann and V. Gill, "Pelvic floor and abdominal muscle interaction: EMG activity and intra-abdominal pressure," *Int. Urogynecol. J.*, vol. 13, no. 2, pp. 125–132, Apr. 2002.

[162] L. Leeman, R. Rogers, N. Borders, D. Teaf, and C. Qualls, "The effect of perineal lacerations on pelvic floor function and anatomy at 6 months postpartum in a prospective cohort of nulliparous women," *Birth*, vol. 43, no. 4, pp. 293–302, Dec. 2016.

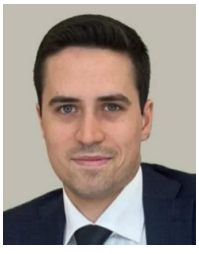
[163] N. Förstl, I. Adler, F. Süß, and S. Dendorfer, "Technologies for evaluation of pelvic floor functionality: A systematic review," *Sensors*, vol. 24, no. 12, p. 4001, Jun. 2024.

[164] K. Ptaszkowski, B. Małkiewicz, R. Zdrojowy, M. Paprocka-Borowicz, and L. Ptaszkowska, "Assessment of the elastographic and electromyographic of pelvic floor muscles in postmenopausal women with stress urinary incontinence symptoms," *Diagnostics*, vol. 11, no. 11, p. 2051, Nov. 2021.

[165] H. K. V. da Silva, M. C. E. Oliveira, E. Silva-Filho, A. G. Magalhães, G. N. Correia, and M. T. A. B. C. Micussi, "Evaluation of the female pelvic floor with infrared thermography: A cross sectional study," *Brazilian J. Phys. Therapy*, vol. 26, no. 1, Jan. 2022, Art. no. 100390.



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