

Crosstalk considerations in studies evaluating pelvic floor muscles using surface electromyography in women: a scoping review

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Abstract

Purpose Surface electromyography (sEMG) using intravaginal probes is of widespread use for assessing pelvic floor muscles (PFM) activity in women. Although considered as a reliable method, its validity has been called into question due to the presence of a phenomenon called crosstalk. Crosstalk is described as the recording of sEMG activity originating from neighboring muscles rather than coming exclusively from the muscles being investigated. The purpose of this review was to provide an overview of existing literature about crosstalk during intravaginal surface electromyographic recordings.

Methods A scoping review was performed according to the Arksey and O'Malley framework. An electronic search was conducted on six relevant databases. Additionally, authors were directly contacted to identify grey literature. Data extraction consisted of descriptive numeric analysis as well as thematic analysis, which were conducted by two independent reviewers.

Results Forty-nine references written by 34 authors coming from 13 different countries constitute the body of evidence of the present review. Eight main themes have been identified through the thematic analysis. The included material varies greatly in terms of methodology, approach to the crosstalk problem and depth of analysis.

Conclusions A gap in knowledge affecting the validity of the current sEMG investigation methods was identified. Literature addressing the crosstalk problem is scarce and often flawed. Definitive conclusions are regularly drawn from an insufficient basis of evidence. Further research is, therefore,

deeply necessary, although it remains unclear whether this issue can be solved at all with current technology.

Keywords Urinary incontinence · Diagnosis · Intravaginal probes · Biofeedback · Physical therapy · Modalities

Introduction

Surface electromyography (sEMG) using intravaginal probes is widely used and considered a reliable method of assessing pelvic floor muscles (PFM) activity in healthy women [1]. However, some authors have questioned its validity, suspecting the presence of crosstalk [2, 3].

The crosstalk phenomenon is described as the detection by the EMG of a signal originating from a neighboring muscle rather than exclusively from the muscle under investigation [4]. It is mostly due to volume conduction of electrical activity [5]. Such a contamination is problematic since it may lead to erroneous interpretation of the signal information [6]. Crosstalk has been extensively investigated in some muscle groups including the quadriceps [7] and the gastrocnemii [8]. Byrne et al. [7] concluded that crosstalk from the vastii did indeed contaminate sEMG recordings of the rectus femoris, while Solomonow et al. [8] were able to estimate that crosstalk accounts for 4–5% of the recorded signal of the gastrocnemii.

In the PFM research field, crosstalk has become a topic of growing interest in the discussion sections of recently published studies [9, 10], with great variability in the manner and the depth in which this matter is treated. Very few authors have attempted to evaluate PFM crosstalk as the main focus of their study [4, 11]. Possible explanations for this limited interest include the particular challenges

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posed by the local anatomical characteristics, as well as the related technical and methodological difficulties in designing an appropriate experiment [4]. Another barrier is the relative taboo still surrounding this intimate body part. As a consequence, there appears to be no consensus between researchers concerning the extent of this problem or on its impact on research findings. Some authors consider crosstalk to be negligible [12, 13], while others view it as a real concern [4, 11] because high levels of crosstalk cast doubt on the validity of experimental studies investigating the effectiveness of PFM interventions.

Based on these observations and to provide an overview of the current state of knowledge, it was decided to undertake a scoping review. According to Levac et al. [14], scoping reviews are powerful tools for synthesizing health research evidence. As an exploratory project, a scoping review allows systematic mapping of the available literature, identifying key concepts and gaps in the research, thus pointing out where further primary research is necessary. Moreover, it is particularly indicated when literature is scarce or diverse [14], as in the present project.

The purpose of this review was to provide an overview of existing literature about crosstalk in sEMG PFM measurements. More specifically, the objectives were to (1) conduct a systematic search of the published and grey literature on the topic, (2) map the characteristics of the material retrieved, (3) summarize evidence regarding the aspects of crosstalk discussed in the literature, and (4) determine whether and (if so) how further research should be conducted.

Methods

Methodology

The research team included two reviewers trained as physical therapists and acquainted with PFM research, as well as a supervisor with expertise in sport science.

The methodology for this scoping review was based on the framework outlined by Arksey and O'Malley [15], also considering subsequent recommendations formulated by Levac et al. [14]. This framework involves five successive key phases, which were strictly followed.

As advocated by Levac et al. [14], the fifth step, the “results presentation”, consists of both descriptive numeric and qualitative analyses. A thematic analysis approach was used for qualitative assessment of the body of evidence. Braun and Clarke [16] defined thematic analysis as a method allowing identification, analysis and reporting of patterns (themes) within data. To this end, the six recommended steps were completed successively. According to Caelli et al. [17], this qualitative study, as a thematic

analysis, falls into the category of “generic approaches”. As such, it does not follow the guiding set of philosophical assumptions characteristic of traditional qualitative approaches. Primary physical therapy research, and, therefore, the articles included in the present review, typically follows a realistic ontology and a positivist epistemology, defined by Bourgeault et al. [18] as the clear assumption that “there is a single reality which can be observed directly”. The present qualitative study touches upon pragmatic epistemology, however, since we acknowledge that “phenomena do operate independently of our ideas, but [that] we must apprehend these phenomena through our [own] ideas” [18]. It was conducted with an inductive, descriptive methodology. Furthermore, because this inductive approach was chosen, data extraction and analysis were not based on a set of a priori defined themes; instead, important and recurrent themes were identified in the body of evidence [19].

Research question

This review was driven by the question: “How is crosstalk taken into consideration in published and unpublished studies evaluating pelvic floor muscles (PFM) using surface electromyography (sEMG) in women?”.

Data sources and search strategy

Searches were performed to query six relevant electronic databases: MEDLINE/Pubmed, EMBASE, CINAHL, PEDro, Cochrane and Google Scholar. These searches took place from week 42 of 2015 until week 46 of 2015. To ensure comprehensiveness, no limits were initially set in terms of date, language or type of material.

At the outset, very specific keywords were combined: (PFM) OR (pelvic floor muscle*) AND (crosstalk/crosstalk/cross talk). Thereafter, search terms were broadened to (EMG) OR (electromyography) AND (PFM/pelvic floor muscle*). This procedure generated very comprehensive results, therefore limiting the probability of missing relevant publications. Each search was adapted to the specific requirements of each database. Subsequently, the reference lists of included articles were screened for further potentially relevant articles. The International Continence Society (ICS) and the International Urogynecological Association (IUGA) were identified as relevant organizations. The meeting abstracts from the years 1999 through 2015 for the ICS conferences and 2003/2005–2015 for the IUGA conferences were carefully checked.

As a last step in finalizing the literature search, personal contact with 18 authors active in the field was established via email, with the aim of identifying further unpublished work on the topic (such as bachelor's, master's, doctoral or

postdoctoral theses). A friendly reminder was sent 2 weeks later in cases of non-response. Six researchers answered, and one additional conference proceeding was retrieved, thanks to these suggestions.

Eligibility criteria

Article inclusion was based on inclusion of the word “crosstalk”, or any of its abovementioned spelling variations, in the full-text versions of all articles with titles that suggested the use of sEMG for PFM activity evaluation in women. When electronic search could not be performed, articles were read in their entirety. Every effort was made to retrieve the full texts of all articles that could not be clearly excluded based upon their title. For articles which could not be obtained through the reviewers’ institutional library, authors or journals were directly contacted.

In accordance with the inclusion criteria, articles in which authors did not use sEMG as a method of investigation and justified this choice by emphasizing its susceptibility to crosstalk were excluded as well.

Data characterization

Descriptive numeric analysis

A spreadsheet was created using Microsoft Excel 2008 to display the relevant characteristics of the studies included in the review. To ensure consistency, a standardized framework was used to extract information.

Thematic analysis

The two reviewers (NF and IK) conducted the thematic analysis independently. All citations about crosstalk (including references) were collected into a table using Microsoft Word 2008. Simultaneously, codes were assigned to each excerpt. When different codes were possible for a given citation, the reviewer made her decision based on the aspect that she perceived as dominant.

After an initial test including the first five articles of the review, both reviewers met to exchange experiences, check the preliminary findings and ensure that the procedure led to satisfactory results. After this meeting, data from the totality of the articles were extracted following the same procedure. Another meeting took place to compare the final results, find consensus on the codes, identify themes and finally define them. Themes were then re-organized, to allow a logical flow to emerge between them. As for the other steps, this stage happened through consensus between the two primary researchers.

Data extraction was systematically conducted from the first to the last reference. Hence, the concept of saturation

was not considered. This procedure ensured comprehensiveness but as a consequence, similar information was collected repeatedly.

Results

Search and selection of studies

The selection process is displayed in a flowchart adapted from the PRISMA guidelines in Fig. 1 [20]. One article was excluded on the grounds that an ambiguous online translation was obtained from the original Icelandic-language text. Only one conference abstract was found through screening meeting abstracts; however, it was already a part of the included references. This is not surprising since the search strategy was designed to generate exhaustive results. The 49 remaining articles were further analyzed and constitute the body of evidence of this scoping review.

Descriptive numeric analysis: general characteristics of the included material

The oldest included article was published in 2001, whereas the most recent dated from 2015. In the majority of cases (61%: 30/49), the mention of crosstalk was only incidental, i.e., limited to one or two sentences on the topic.

Overall, 34 different first authors contributed to the topic of interest, with 8 of them writing more than one included reference. However, additionally taking into consideration the last authors, it is noteworthy to point out that many references are the result of the work produced by only a few research teams that have been extremely active in this field. This is highlighted in Table 1.

Details about types of documents, study designs, localization of the statements regarding crosstalk and types of intravaginal probes are shown in Table 2.

Themes identified through thematic analysis

Results of the thematic analysis are presented in a complementary fashion in the text and in Table 3, which presents the different themes and subthemes identified, providing direct citations as illustrative examples from the body of evidence.

1. Definition of the concept

1a. Description

As introductory sentences, some authors provide a brief description of the phenomenon [4, 21].

Fig. 1 Flowchart of the literature search methodology [20]



PRISMA 2009 Flow Diagram

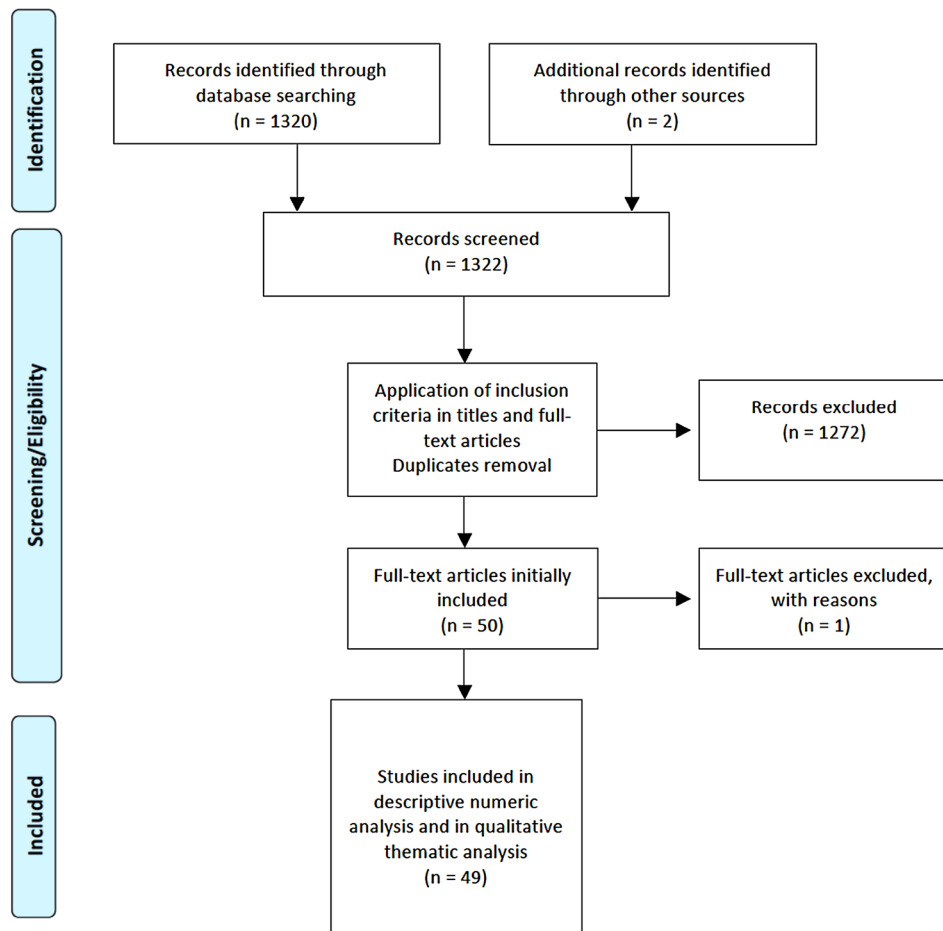


Table 1 Main supervisors and their number of included material

| Supervisor/last author | Number of included references |
|--------------------------|-------------------------------|
| McLean Linda | 17 (35%) |
| Hodges Paul | 6 (12%) |
| Bo Kari | 3 (6%) |
| Radlinger Lorenz | 3 (6%) |
| Diniz Zanetti Miriam | 2 (4%) |
| Other (1 reference only) | 18 (37%) |
| Total | 49 (100%) |

1b. Contamination (muscles involved)

Although defining which muscles are susceptible to generating crosstalk is of paramount importance, only two references relay this valuable information [4, 11].

1c. Rationale for recording crosstalk

Regarding the reasons underlying crosstalk recording, current PFM literature is somewhat scarce [2].

2. Current research and evidence

Authors actively seeking to address the crosstalk problem perceive the actual state of knowledge and the few underlying studies very critically, as the current state of research is described as “inadequate” and “misleading” [2, 4].

3. Influencing factors

3a. Intravaginal probes

In comparison with other techniques available to record PFM activity, intravaginal probes present practical as well as technical benefits related to crosstalk [2]. Other authors make reference to previously published work to justify the adequacy of their choice of assessment method [22].

Table 2 Types of documents and study designs, localization of statements and types of intravaginal probes included in the scoping review

| Type of document, number (%) | Study design, number (%) | Localization of the statements, number (%) | Type of intravaginal probe, number (%) |
|----------------------------------|--------------------------|--|--|
| Indexed Journal Article 34 (70%) | Cross Sectional 28 (57%) | Discussion 33 (42%) | Periform 16 (32%) |
| MSc thesis, unpublished 7 (14%) | Longitudinal 13 (27%) | Methods 19 (25%) | Femiscan 16 (32%) |
| PhD Thesis, unpublished 5 (10%) | Review 8 (16%) | Introduction 14 (18%) | Other 12 (24%) |
| Conference proceeding 3 (6%) | | Literature review 4 (5%) | Prototype: DSE 4 (8%) |
| | | Results 4 (5%) | Not mentioned 2 (4%) |
| | | Conclusion 3 (4%) | |
| | | Commentary 1 (1%) | |
| Total: number (%) 49 (100%) | 49 (100%) | 78 (100%) ^a | 50 (100%) ^b |

^aThe total does not add up to the usual 49 because on some occasions, more than one statement pertaining to crosstalk could be included

^bThe total does not add up to the usual 49 because on some occasions, more than one probe was used, whereas other included references such as reviews did not directly make use of intravaginal probes

3b. Electrode configuration

To minimize the likelihood of recording crosstalk, differential electrode configurations should be favored. In contrast, monopolar configurations record activity from a large surface, thereby increasing the probably of crosstalk and noise [10, 23, 24].

3c. Electrode size and location

Ideally, surface electrodes should be small in size and inter-electrode distance should be kept short [25, 26].

3d. Other factors

Additional relevant aspects to consider include temperature and humidity [2]. However, these factors are quite difficult to control.

4. Investigation/identification

4a. Crosstalk present: quantification/assessment

Only two researchers (Madill [11, 27] and Keshwani [4, 10]) explicitly attempted to bring to light the presence of crosstalk in their recordings. A few others conducted separate sub-studies including very few subjects (Hodges et al. [13], Sapsford and Hodges [28], Smith et al. [29], Sjödaahl et al. [30]). Madill [11, 27] compared increasing PFM EMG activity amplitude with increasing vaginal pressure amplitude during isolated and non-isolated PFM contractions. Besides the PFM, she examined the transversus abdominis, the rectus abdominis, the gluteal and hip adductor muscles. When intravaginal pressure did not increase simultaneously with rises in EMG amplitude, crosstalk was deemed present. Madill [11, 27] found this to happen in two of eight subjects, being the first researcher to introduce the possibility of individual variability in crosstalk recordings. Keshwani and McLean

[10] additionally draw attention to the influence of contraction intensities of the hip muscles, as the risk for crosstalk has been shown to increase concomitantly with higher intensity levels. In a further publication [4], Keshwani and McLean analyzed PFM EMG activation amplitude using Root Mean Square (RMS) during hip adductor and hip external rotator ipsilateral muscle contractions. They compared a newly developed suction head intravaginal probe with the commercially available Femiscan, concluding that both intravaginal probes were susceptible to recording crosstalk at higher levels of contraction intensities, i.e., during contractions exceeding 50% of maximal voluntary contraction (MVC). However, they were not able to firmly determine if both probes were recording crosstalk, or if this increase in activity was due to co-activation (see also point 5).

4b. Reasons for crosstalk exclusion

Sjödaahl et al. (unpublished; in Sjödaahl et al. [30]) have conducted a separate pilot study to investigate PFM crosstalk from the abdominal and hip adductor musculatures. They concluded that the risk for crosstalk is minimal. Unfortunately, despite our best efforts, we could not access this publication. Hodges et al. [13] examined crosstalk by simultaneously recording vaginal PFM activity levels using a Periform probe and activity of the gluteus maximus, hip adductors, medial hamstrings, obliquus internus abdominis and rectus femoris muscles using surface EMG electrodes. The study protocol involved one subject during the performance of one low-intensity arm movement task. Under these circumstances, no crosstalk from the hip or abdominal musculature has been observed. Smith et al. [29] reported about a very similar protocol performed

Table 3 Identification and organization of themes and subthemes

| |
|---|
| 1. Definition of the concept |
| 1a. Description |
| “Crosstalk is the extent to which EMG electrodes record muscle activation from muscles other than the muscle of interest” [21] |
| “Crosstalk occurs when electrodes detect signals that originate from nearby muscles rather than solely from the muscle of interest” [4] |
| 1b. Contamination (muscles involved) |
| “With respect to recording EMG from the PFM, nearby muscles that may contribute to crosstalk include the hip external rotators (particularly the obturator internus which forms an attachment for portions of the PFM), the hip adductors, the gluteals, and the deep abdominal muscles (i.e. the transversus abdominis)” [4] |
| 1c. Rationale for recording crosstalk |
| “Due to the volume conducting nature of the body tissues, impulses generated from muscles other than the target muscle can be recorded by electrodes placed over the target muscle” [2] |
| 2. Current research and evidence |
| “However, reports of crosstalk (or the absence of crosstalk) are not adequately addressed in the literature, and are even misleading” [2] |
| “Thus far, the majority of studies investigating the presence of crosstalk when using an intravaginal probe to record surface EMG from the PFM have used small sample sizes of one or two subjects, and have only investigated low intensity contractions of neighboring muscles. In these cases, no crosstalk was detected from the internal oblique abdominals, rectus femoris, hip adductors, gluteus maximus or medial hamstrings when recording EMG from the PFM. It is important to note that although obturator internus is the most likely source of crosstalk, the external rotators were not included in the above studies” [4] |
| 3. Influencing factors |
| 3a. Intravaginal probes |
| “Detecting the myoelectrical activity closer to the surface of the deep PFM has the potential to give the researchers valuable information for quantitative analysis while controlling for the filtering effect on the signal travelling through multiple layers of soft tissue, thus decreasing crosstalk” [2] |
| “A Lifecare Vaginal Probe PR-02 (Everyway Medical Instruments Co., Ltd., Taiwan) was used (...) it has been reported to record PFM activity with minimal crosstalk during tasks” [22] |
| 3b. Electrode configuration |
| “The disadvantage of a monopolar electrode configuration is that the resultant signal is prone to noise and crosstalk since there is often a large distance between the electrodes, which means that activity recorded from nearby muscles looks different to each of the recording electrodes and is therefore not subtracted. In order to decrease the likelihood of recording crosstalk, differential electrode configurations are recommended. (...) Although the differential configuration is generally superior to the monopolar configuration in that it is less prone to crosstalk and noise, only one of the commercially available intravaginal probes, the Femiscan, employs a differential electrode configuration” [10] |
| 3c. Electrode size and location |
| “Crosstalk is even more likely to occur when the electrodes are large in size or when the active electrode and reference electrode are spaced far apart, as both factors increase the ability to record activity from muscles farther away” [26] |
| 3d. Other factors |
| “The skin temperature and amount of humidity in the air will also influence the signal characteristics to some extent” [2] |
| 4. Investigation/identification |
| 4a. Crosstalk present: quantification/assessment |
| “Since pressure did not increase coincidentally with these rises in EMG amplitudes, these findings suggest that contraction of these muscles may have resulted in crosstalk in some subjects, but not in others” [27] |
| “The Femiscan electrodes record crosstalk from the hip musculature at contractions levels greater than 25%” [10] |
| 4b. Reasons for CT exclusion |
| “We have also investigated the possibility of cross-talk between the abdominal muscles and the PFM as well as between the hip adductors and the PFM in a pilot study (unpublished). If the correlation between the EMG activation of the PFM and the deep abdominal muscles or between the PFM and hip adductors could be visually detected, recording the EMG activity of the PFM could be a risk for cross-talk. No such correlations were detected in the pilot study suggesting that the risk of crosstalk was minimal” [30] |
| “Raw data shows that with contractions of this intensity, there was no cross-talk from the hip and abdominal muscles recorded with the vaginal electrode” [13] |
| “This demonstrates that activity of adjacent muscles is unlikely to affect PFM EMG recordings” [29] |
| “For both vaginal electrodes, the cross-correlation coefficients between the abdominals and PFM were less than 0.90, suggesting that cross-talk between the deep abdominals and PFM was not a concern” [26] |
| 5. Synergistic activation |
| “No conclusion can be made regarding whether the activity recorded from the PFM during maximal hip adduction and external rotation is the result of crosstalk or co-activation” [4] |
| “It is not possible to determine whether this increase in PFM EMG activity is the result of co-contraction or crosstalk from the research that is currently available” [21] |

Table 3 (continued)

6. Limitations of sEMG (with regard to crosstalk)

6a. General

“Surface EMG of the PFM has been criticized because of the possible influence of cross-talk from other muscles. Hence, such studies must be interpreted with caution” [32]

“The use of surface EMG has various limitations. It is subject to crosstalk” [31]

“Although EMG is a reliable method of assessing PFM activity in healthy women, crosstalk can confound the interpretation of EMG recordings using a bipolar surface electrode arrangement” [9]

6b. Psychometric properties (validity and reliability)

“However, in spite of acceptable reliability, the validity of sEMG can be questioned, mostly due to the high risk of cross-talk from nearby muscle groups” [33]

“If cross-talk interferes with the ability to record EMG activity within the PFM, then this technique of studying neuromuscular activation and synergies to understand the biomechanics of urinary incontinence is not valid” [27]

“If appropriate measures are taken to minimize the impact of crosstalk, variability in electrode placement and environmental noise and motion artifact, and if normalization procedures are carefully applied and cautiously interpreted, surface EMG can provide a reliable measure of activity in the PFM within a given day” [24]

7. Measures taken to avoid crosstalk: Development in the text

8. Suggestions for future work: development in the text

on one continent woman, coming to the same conclusion.

Keshwani [26], in her Master’s thesis investigating the re-test reliability and validity of a novel suction electrode in comparison to the Femiscan, was able to conclude that crosstalk from the deep abdominal muscles could be excluded.

Sapsford and Hodges [28] used a Periform vaginal probe and sEMG electrodes over the hip adductors and the gluteus maximus. They visually compared the onset times of muscular activity and concluded that crosstalk was unlikely, since they identified distinct activity patterns.

5. Synergistic activation

A major issue in current research is being able to make a distinction between crosstalk and synergistic activation (or co-activation) of neighboring muscles. As a matter of fact, the PFM might be activated to assist in pelvic stabilization during resisted tasks, and probably work in synergy with other muscles of the pelvic girdle [2]. However, as of today, researchers have not been able to develop a methodology to differentiate between them.

6. Limitations of sEMG (with regards to crosstalk)

6a. General

Very often, crosstalk is simply incidentally mentioned in similar recurrent formulations urging readers to use caution in the interpretation of the results due to the possibility of crosstalk [9, 31, 32].

6b. Psychometric properties (validity and reliability)

If proven true, crosstalk poses a threat to the validity of measurements [27, 33].

As to reliability, opinions are unanimous, taking the view that intravaginal probes provide reliable results during a single day [24].

7. Measures taken to avoid crosstalk

Some authors decided to make adjustments or take additional precautionary measures in order to minimize the potential for crosstalk. These preventive actions included: visual inspection to identify simultaneous hip adductor or gluteus muscle contraction instead of isolated PFM contraction [34–36]; use of a strap in the lithotomic position to support legs and prevent contraction of the hip internal rotators or adductors [24]; completion of additional pilot studies to assess the problem [13, 28–30] and teaching of a correct isolated PFM contraction and screening for the ability to perform it before study enrollment [35].

8. Suggestions for future work

Many aspects of the problem have been overlooked or could not be taken into consideration so far in the literature. Future work should especially focus on the following points:

Use electrodes large enough to record a reasonable amount of activity, but small enough to minimize crosstalk [37].

Use a bipolar configuration combined with a differential amplifier, and provide extensive details about signal processing methods [2].

Minimize inter-electrode spacing [24].

Favor probes providing double differential electrode configuration [26].

Treat results from the right and the left sides of the PFM separately, differentiate between contraction

intensity levels (% of MVC) and consider hip external rotators in the evaluation protocol [26].

Teach correct isolated PFM contraction beforehand, and check for accessory muscle contraction or movement at the hip joint [21].

Discussion

Although the first report of using EMG to describe female PFM activity goes back to 1968 [38] (cited in [27]), it must be recognized that this method still has potential for improvement with respect to crosstalk considerations. The inconsistency in spelling, with different variants (“crosstalk”/“cross-talk”/“cross talk”) sometimes encountered in a single article, is a prime example of the vagueness surrounding the topic. Another worrisome characteristic of the current literature is that it mainly relies on subjective, qualitative inspection of raw data [13, 30], whereas scientific rigor would call for objective methods including statistical analysis. The present scoping review sheds light on the contrasting opinions held by researchers. It is interesting to notice that often, authors who state their confidence in the ability of intravaginal probes to record PFM activity without capturing crosstalk [22, 30, 39–42] make reference to only two studies from the same research group [13, 29], which present the major drawback of being underpowered. They both included only one healthy subject for the crosstalk investigation. Moreover, on at least one occasion, a researcher arguing that the intravaginal probe used in his study had been previously tested and was not prone to crosstalk based his statement on three references [22]. Interestingly, a brief verification into the source articles revealed that none of the three publications in fact investigated this particular type of intravaginal probe. Such a basis is insufficient to draw definitive conclusions on this complex matter. On the other hand, authors arguing that current intravaginal probes are subject to crosstalk deserve credit for basing their opinions on more comprehensive research, describing issues and actively looking for alternatives (Keshwani [4, 26], Madill [11, 27], McLean [43]). Since they could not be satisfied with the commercially available probes, some authors decided to create their own prototypes [43–45]. To date, those prototypes have not been commercialized.

Limitations

Overall, the high proportion of references making incidental mentions of the crosstalk phenomenon is regrettable:

many authors did not look thoroughly into the problem, instead repeatedly using similar warning statements.

One author, who claimed to have conducted a pilot study with the express purpose of investigating the crosstalk problem, never responded to our request for the text of this study. This unpublished article might have brought additional insights into the topic being discussed.

Scoping reviews by definition are to be conducted without performing any kind of quality assessment of the included material. This guarantees breadth of coverage, but a lack of methodological rigor in the primary material suggests that readers ought to exercise caution in the interpretation and generalization of the present findings.

Suggestions for future research

The challenges faced in designing the perfect intravaginal probe while considering crosstalk issues, among others, are numerous and diverse. Not only do the deep PFM lie in an intimate and sensitive area hidden within the pelvic cavity, but also the moist environment of the vaginal canal precludes the use of traditional adhesive electrodes [2, 26]. Hormonal changes influencing vaginal humidity and varying temperature may also be sources of signal alteration [10]. Individual components, with the presence of crosstalk being identified in some subjects but not in others, cannot be excluded [27]. The ability to voluntarily contract the PFM is far from straightforward to many healthy individuals [2]. Furthermore, obtaining a true maximal voluntary contraction is crucial in any sEMG activity recording, but for the PFM any potential pain or fear of pain, discomfort, anxiety or feeling that the probe may slip out further complicates this requirement [2]. Moreover, the very presence of the vaginal probe may alter PFM performance by modifying their contractile properties, although Auchincloss and McLean showed that it probably does not have such a significant influence [46]. The adaptability of the intravaginal probe to each subject’s particular anatomical characteristics and gynecological/obstetrical history may play a key role, though an underappreciated one. Indeed, the two most commonly used, commercially available intravaginal probes (the Periform and the Femiscan) surprisingly only come in one standard size despite the fact that Voorham-Van der Zalm et al. [47], back in 2006, were able to show using ultrasound that probe positioning varied considerably among multiparous women. This positioning problem is further complicated by the observation that the PFM move cranially and ventrally while they contract [26]. Additionally, the fact that most probes were originally designed for biofeedback therapy purposes in lithotomic position makes them susceptible to motion artifacts and therefore inadequate for use while standing, during functional tasks such as coughing, or during whole-body movements

accompanied by reflexive activity of the PFM, such as running and jumping. Another important consideration is the sometimes forgotten characteristic that both sides of the PFM are different muscles with distinctive innervations, and as such, an adequate intravaginal probe should be able to distinguish between right and left sides [2]. Ignoring this would provide an erroneous, nonspecific representation of the general muscle activity around the vagina [26]. Double differential configuration, as advocated by the SENIAM group (Surface Electromyography for the non-invasive assessment of muscles), as well as small electrode surfaces located close together, are additional requirements to be fulfilled to minimize crosstalk [48]. Other issues such as the distinction between synergistic activations or substitutions and crosstalk imply a high degree of methodological complexity in the elaboration of an adequate research protocol. This will require interdisciplinary collaboration among the engineering sciences, mathematics, and so on.

Alternatives to intravaginal probes include the use of adhesive electrodes over the peri-neal area or the insertion of fine wire electrodes. Adhesive electrodes have been shown to account for technical problems related to any possible shift, and also have low subject acceptability [31]. Fine wire electrodes have been chosen for crosstalk investigation in other skeletal muscles: Byrne et al. [7] chose to compare fine wire and sEMG recordings of the rectus femoris and vastus lateralis during isometric contractions consisting of knee extensions and hip flexions. They concluded that crosstalk contamination occurred from the vastus lateralis and suggested utilizing fine wire electrodes to ensure accurate EMG recordings [7]. However, fine wire EMG is particularly invasive, which presages difficulties in participant recruitment. Additionally, it appears not to provide valid results for PFM evaluation since it records only from a very small, localized region (limited to one or two motor units), therefore failing to reflect the global muscle activity [10]. For these reasons, neither adhesive nor fine wire electrodes can be considered valid options. Therefore, further research should focus on testing and establishing a valid reference intravaginal probe. In addition, improvements regarding the electrodes, the measuring amplifiers and the development of adequate mathematical methodologies, such as Wavelet Transforms or Empirical Mode Decomposition [49] to purify the signal from crosstalk contaminations are appropriate leads to pursue in the future. The gain of a non-stationary wavelet approach is to provide simultaneous information in the domains of time, frequency and magnitude. Therefore, areas where the muscles co-contract can be distinguished. The areas where the activity of individual muscles predominates indicate the maximal expected amount of crosstalk [50]. The Empirical Mode

Decomposition (EMD) is a method for breaking down signals into various components and comparable with Fourier transform and Wavelet transform. Without leaving the time domain, EMD is adaptive and can be applied to non-linear and non-stationary time series, i.e., derived from ECG or EMG. Together with subsequent independent component analysis [51] it can be used to purify EMG from ECG artifacts [51], electrical muscle stimulation signals [52] or crosstalk [53]. However, from a global perspective, an essential and somewhat daunting question remains open: even if a perfectly optimized intravaginal probe was available, since some highly crosstalk-susceptible muscles—such as the hip external rotators—are not accessible to direct sEMG measurements, it might be impossible to detect and remove their influence using current technology.

Conclusions

This scoping review identified a gap in scientific knowledge regarding the validity of the diverse intravaginal probes currently used in research. Literature addressing the crosstalk problem is scarce and oftentimes flawed: studies in this area suffer from having a small number of subjects involved in the evaluation procedure. Further deficiencies include lack of details regarding the protocol, making subsequent independent interpretation difficult, paucity of “reference publications” on the matter and failure to acknowledge and determine the influence of crosstalk from hip external rotators. Considering all these shortcomings, further research is deeply necessary to improve the validity of applied research assessing and comparing the effects of different physical therapy regimens and to deepen the understanding of PFM activation patterns under physiological and pathological conditions. To achieve this goal, the processing of a valid intravaginal probe is required and the method to eliminate crosstalk has to be improved. Nevertheless, it remains unclear to what extent technological tools are sufficient to detect and eliminate crosstalk signal contaminations in future. However, the leading question persists whether this issue can be solved at all with current technology.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants performed by any of the authors. Therefore, for this type of study formal consent is not required.

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