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A switched system for modeling the interaction of pleasure and pain in vaginal dilation exercises

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Abstract: Genito-pelvic pain/penetration disorders, i.e., painful experiences during penetrative sexual intercourse, affect an estimated 30–40 % of people with vaginas at some point in their lives. Treatments for Genito-pelvic pain/penetration disorders vary depending on the main cause of the condition but may include the use of vaginal trainers/dilators which are used to stretch the vaginal duct and relax the Pelvic floor muscles. As a step towards understanding how patients respond to vaginal trainers, we investigate the interaction of pain and pleasure characteristics during treatments. In this paper, we adapt an existing qualitative model into a switched system where switches are determined by a patient's subjective level of pleasure. A qualitative model of the pain and fear characteristics is derived for each switched state. Due to sparsity in the experimental data, we adopt a weighted least squares approach for parameter identification using online (constant sampling period) and offline data (sparse and inconsistent sampling). The results indicate that it is a promising method compared to the grey-box model without considering pleasure levels but there is an obvious and variable delay in the reporting of a patient's pleasure levels which affects the overall performance of the switched system.

Keywords: Biomedical system modeling, Identification and validation, Decision support systems for the control of physiological and clinical variables

1. INTRODUCTION

Genito-pelvic pain/penetration disorders (GPPPDs) are known to have a substantial impact on the physical, psychological, and relational health of people with vaginas and can often manifest as a profound emotional disturbance of mental illness (Hayes et al., 2008; Kaplan, 1980). It is estimated that 30 % to 40 % of people with vaginas will suffer from a prolonged period of painful sexual intercourse at some point in their lives (Goldstein et al., 2009, Chap. 2)). GPPPDs may arise from complications after cervical cancer surgeries, vaginal radiation therapies, menopause, gender affirmation surgeries or conditions such as dyspareunia and vaginismus, caused by fear of pain during genital penetration (Melles et al., 2018).

Treatments for GPPPDs often include both psychological perspectives, e.g., Cognitive Behavioral Therapies (CBTs), and physiological treatments such as the use of Vaginal Trainers (VTs) used to stretch the vaginal duct, desensitize the vestibulum, and relax the Pelvic floor muscles (PFMs) (Binik et al., 2006; Bergeron et al., 2008; Goldstein et al., 2011). VTs, a.k.a., vaginal dilators, are tube-shaped devices ranging from small (the size of a finger) to large. The use of VTs in the treatment of GPPPDs is considered to be invasive, and lengthy, and many women experience intense pain and failure when adhering to their therapy plan (Macey et al., 2015). Consequently, treatment dropout rates are high, and patients are often forced to live with their debilitating disorder. This leads to an obvious societal need to better understand the underlying factors behind pleasure and pain during GPPPD treatment and how to mitigate negative effects. In this paper, we tackle the first steps in achieving the goal of developing a holistic healthcare treatment for GPPPDs.

1.1 Literature Review

There currently exist many established models for both healthy sexual responses and the responses of people with GPPPDs in the sexology literature. Starting with the known models of healthy sexual responses in females, it was shown that physiological arousal initiates genital blood flow leading to vasocongestion of the vestibular bulbs and vaginal lubrication (Puppo, 2013; Levin, 2002), implying that lubrication can be interpreted as a direct measure of physiological arousal. Further, stimulation of the clitoral complex including the vestibular bulbs is

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known to facilitate and intensify orgasms (Puppo, 2011). As for the subjective side – and thus the psychological part of the sexual response – two different theoretical frameworks can be considered: the incentive motivation model and Basson's model. A large part of the literature on female sexuality and desire ladders on Basson's non-linear model of the female sexual response (Basson, 2000). Basson's model states that subjective sexual arousal is affected by several psychological inputs; for example, satisfaction with the relationship, self-image, previous, negative sexual experiences, negative cognitions, and focus of attention. Moreover, subjective arousal is highly influenced by the subjective, cognitive appraisal of the stimuli. Basson's model, however, is considered to be outdated and highly critiqued. The incentive motivation model by Both, Erveraed, and Laan rather emphasizes the role of external stimuli and incentives that serve as triggers for sexual desire (Both et al., 2007). In other words, a sexual stimulus will not automatically trigger genital arousal. Once a woman is aware of physiological signs of arousal, they begin to consciously evaluate the sexual stimulus and assign meaning to it (linking to sexual memories) which then leads to a subjective sense of arousal and motivation to do something with it or to act on it. These associations with the external stimuli are then reinforced by pleasurable sexual experiences. Hence, the feedback between genital and subjective arousal is important because the subjective evaluation of the genital response determines whether the sexual response unfolds into a full sexual response.

As for the dynamics of genital pain during penetrative intercourse, it is known that fear induces activity of the pelvic floor muscles (van der Velde et al., 2001; Both et al., 2012). Then, if the pelvic floor muscles are active when attempting vaginal penetration, both lubrication and vasocongestion levels decrease since the increased pressure on the vulvar and vaginal skin leads to reduced blood flow and lubrication (Van Lunsen and Ramakers, 2002; Binik et al., 2006). Importantly, this relationship depends on the timing: initial stages of arousal lead to an initial relaxation of the pelvic floor. Then, as arousal increases, the deeper-located pelvic floor muscles contract to achieve the orgasmic phase. Still, these contractions do not affect the lubrication and vasocongestion (Both et al., 2012). The previous implications then suggest that low physiological arousal or overactive pelvic floor muscles (i.e., pelvic floor hypertonicity) leads to genital pain when penetration is attempted. This logical chain is consistent with other existing medical literature on the subject, e.g., Brauer et al. (2006); Farmer and Meston (2007); ter Kuile et al. (2010).

Indeed, all the models in the medical literature discussed focus on understanding implications and cause-effect relationships; in this specific field of medicine, though, there is a lack of mathematical models that can be used to forecast when a specific person will start for example developing unbearable pain if subject to some specific stimuli. Towards closing this gap, Varagnolo et al. (2017) proposed a model to describe the dynamics of the pressure vs. pain mechanisms employing opportune state space representations and hence derived a novel qualitative, dynamical model that allows control-oriented analyses of pressure and arousal dynamics. Jackson et al. (2024) then took the first steps in validating the proposed model by using data collected with applied vaginal pressure to identify the pain and fear characteristics in the sexual response to vaginal pressure and visual stimuli. Knorn et al. (2018) moreover propose a quantitative model for forecasting patients' pain and pleasure levels based on changes in vaginal dilation.

Due to the lack of measurement data for the pleasurable response to vaginal pressure in Melles et al. (2018), there is still no established model for describing the impact of pleasure on the pain and fear responses during penetrative intercourse. This manuscript extends the work in Jackson et al. (2024) combined with the work in Knorn et al. (2018) to study the impact of the vaginal pressure stimulus on both pleasure and pain characteristics in sexual intercourse.

1.2 Statement of Contributions

In this paper, we:

- propose a new switched system for incorporating the effect of subjective levels of pleasure on the dynamic models of the exasperation of pain and fear during vaginal dilation exercises;
- identify an instance of this model based on data from a medical trial involving several patients;
- assess the predictive capabilities of the model on unseen data from the same dataset; and
- compare such performance against previously established black-box and grey-box models developed and tested in Jackson et al. (2024).

1.3 Organization of the Manuscript

We continue in Section 2 by describing the experimental setup, the dilation device, and the measurements. In Section 3, we present the current state-of-the-art in dynamic modeling of fear and pain characteristics with vaginal dilation and propose a switched model to extend upon the current work to include the impact of subjective pleasure on the response. We follow in Section 4 by presenting the fit values compared to the results in Jackson et al. (2024). Conclusions are drawn in Section 5.

2. MEDICAL TRIAL SETUP AND DATA

Medical trials were executed at Maastricht University Hospital to investigate how the PFM respond to forced vaginal dilation (Melles et al., 2018). The data in this trial comprises the responses of healthy women to the gradual vaginal dilation induced by an inflatable balloon inserted at the introitus while watching sequences of different 5-minute-long erotic or non-erotic films in a controlled laboratory environment. The medical device is called a Vaginal Pressure Inducer (VPI), shown in Figure 2.

2.1 Participants and Experimental Protocol

The study included 42 healthy women aged between 18 and 45 years who had been in a steady heterosexual relationship for at least 3 months, and who in this period had been sexually active including coitus. Each woman participated in individual sessions where they recorded their

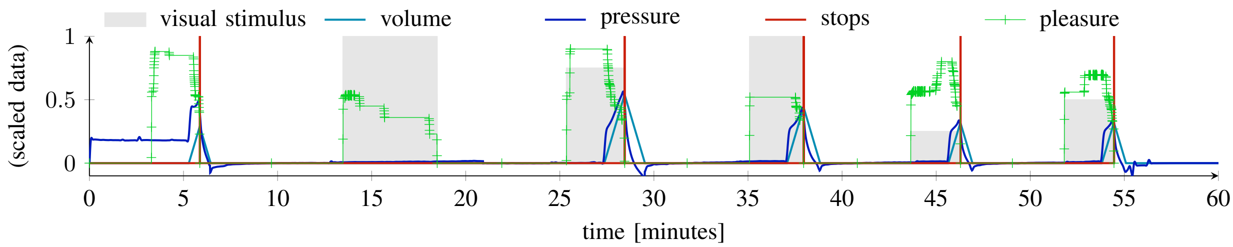


Figure 1. A typical dataset selected randomly from one of the patients. The six films above are neutral (acclimatization), high arousal and sexual (control condition), low arousal and sexual (0.75), high arousal and sexual (1), low arousal and non-sexual (0.25), high arousal and non-sexual (0.5). The films started at minutes 3, 13, 26, 35, 43 and 52, respectively. Inflation levels of the VPI are plotted by means of the "volume" curve, while pressure measured in the balloon is plotted by means of the "pressure" curve. The "pleasure" curve reports the subjective experience of the patient, measured by the patient by means of a slider. The crosses in this curve indicate when in time the patient actually touched the slider. The "stops" vertical bars indicate when the patient early-terminated the experiment, i.e., manually triggered an instantaneous deflation of the VPI. The data is min-max scaled.

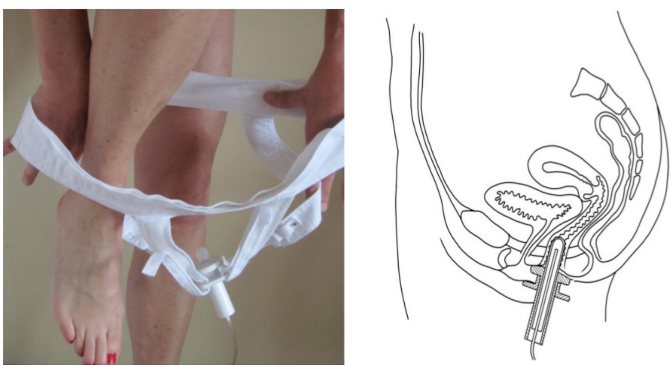


Figure 2. Picture of the VPI (left) and schematic description of its utilization (right). The balloon is gradually filled with water by a controlled pump. When the balloon is filled, an outward and uniform pressure is applied to the vaginal duct. The device measures a corresponding exerted pressure by sensing the force exerted by the pump at any time.

perceived level of pleasure with an opportune slider while wearing the VPI and watching pre-defined film sequences. Importantly, the participants could prematurely end the experiments with a stop button as soon as the pressure level felt unpleasant– forcing an instant deflation of the balloon.

Each session started with an acclimatization phase including the expansion of the VPI followed by showing a high-arousal sexual film without inducing vaginal pressure (the control condition). Afterward, each woman watched four films (a high-arousal & sexual, a low-arousal & sexual, a high-arousal & nonsexual, and neutral) in random order with pressure induced by the VPI and intermittent distraction tasks.

2.2 The Data Collection

During the experiment, the induced pressure in the water balloon was measured at the pump as an indirect measure of the pelvic floor muscle activity at a frequency of 2 Hz. The reported subjective pleasure (on a scale between 0 and 100) was also recorded as well as the times when patients stopped the experiment to force the deflation of the balloon. A typical sample of the corresponding time series is shown in Figure 1.

3. A MODEL FOR THE INTERACTION PLEASURE AND PAIN

In this section, we discuss the state-of-the-art in dynamic modeling of sexual responses and the associated identifiability issues of the proposed models. We further propose a switched system to avoid the identifiability issues of the data.

3.1 The Existing Model

Varagnolo et al. (2017) proposed a model to describe the dynamics of pleasure and arousal response to visual stimuli and vaginal pressure called the Circle Of Pleasure (COP), seen on the left side of Figure 3 and the pressure vs. pain mechanisms referred to as the Circle Of Fear (COF) and presented visually on the right side of Figure 3.

This model assumes erotic stimuli to inhibit fear by diminishing fearful thoughts. Pressure stimuli are instead assumed to stimulate muscular tension, and thus potentially lead to pain. Depending on the psychophysical status, pressure stimuli are thus supposed to potentially lead to pain or pleasure (Varagnolo et al., 2017).

Circle of Fear Referring to Figure 3, the right part of the model describes the feedback loop between fear, muscular tension, and pain by means of

$$\begin{cases} \dot{x}_{\text{pain}} = -\theta_1 x_{\text{pain}} + \theta_2 \sqrt{x_{\text{muscles}}}\, u_{\text{pressure}}, & \text{(1a)} \\ \dot{x}_{\text{muscles}} = -\theta_3 x_{\text{muscles}} + \theta_4 x_{\text{fear}}, & \text{(1b)} \\ \dot{x}_{\text{fear}} = -\theta_5 x_{\text{fear}} - \theta_6 x_{\text{fear}} u_{\text{stimulus}} + \theta_7 x_{\text{pain}}\,. & \text{(1c)} \end{cases}$$

Here, $\theta \in \mathbb{R}^{11}_{\geq 0}$, $x_{\text{COF}} = [x_{\text{pain}}\ x_{\text{muscles}}\ x_{\text{pain}}]^\top \in \mathbb{R}^3$, and $u = [u_{\text{pressure}}\ u_{\text{stimulus}}]^\top \in [0,1]$. In (1a) we use the term $\sqrt{x_{\text{muscles}}}\, u_{\text{pressure}}$ to model the assumption that with applied vaginal pressure, pelvic muscle activity before or at the beginning of penetration may lead to pain in the patient which is compliant with the findings in Paterson et al. (2013). Equation (1b) captures the fact that fear leads to muscular tension. Equation (1c) models the fact that pain solicits fear. The effects of erotic stimuli are included as a way to temper fear. Thus, if the patient is

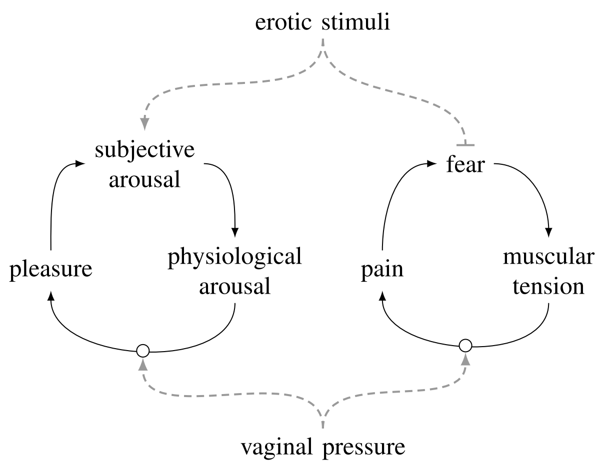


Figure 3. Left: The Circle Of Pleasure (COP) for modeling the interaction of pleasure and arousal to erotic stimuli and vaginal pressure. Right: The Circle Of Fear (COF) modeling the exasperation of pain and fear as a response to vaginal pressure.

being stimulated, i.e., $u_{\text{stimulus}} > 0$, while feeling fear then $x_{\text{fear}} u_{\text{stimulus}}$ acts as a fear-reduction mechanism. Finally, we note the origin is an asymptotically stable point; this captures the intuition that in the absence of external stimuli, the person should ideally arrive at a neutral resting condition.

We postulate that the measurement data about vaginal pressure and stop events (the likelihood of the occurrence of events where patients decide to stop the inflation of the VPI and force its deflation) are measurements of opportune transformations of the variable x_{COF} in the following sense:

$$\begin{cases} y_{\text{pressure}} = \theta_8 x_{\text{muscles}} + \theta_9 u_{\text{pressure}}, & \text{(2a)} \\ y_{\text{stop}} = \theta_{10} x_{\text{fear}} + \theta_{11} x_{\text{pain}} \,. & \text{(2b)} \end{cases}$$

Equation (2a) captures the consideration that the measurement is the total pressure at the end of the water pipe connecting the VPI with its pump. The quantities resisting this pressure are the actual pressure stimulus applied to the vaginal duct and the reaction from the muscles. Equation (2b) instead, models that a patient presses the stop button due to a combination of pain and fear.

Circle of Pleasure The left part of Figure 3 models the so-called COP, i.e., the feedback loop between physiological arousal, subjective arousal, and pleasure. The Ordinary differential equations (ODEs) relative to this part of the dynamics are

$$\begin{cases} \dot{x}_{\text{phys}} = -\phi_1 x_{\text{phys}} + \phi_2 x_{\text{subj}} u_{\text{stimulus}}, & \text{(3a)} \\ \dot{x}_{\text{pleasure}} = -\phi_3 x_{\text{pleasure}} + \phi_4 x_{\text{phys}} u_{\text{pressure}}, & \text{(3b)} \\ \dot{x}_{\text{subj}} = -\phi_5 x_{\text{subj}} + \phi_6 x_{\text{pleasure}} + \phi_7 u_{\text{stimulus}} \,, & \text{(3c)} \end{cases}$$

where $\phi \in \mathbb{R}^7_{\geq 0}$, $x_{\text{COP}} = [x_{\text{phys}} \; x_{\text{pleasure}} \; x_{\text{subj}}]^\top \in \mathbb{R}^3$, and $u = [u_{\text{pressure}} \; u_{\text{stimulus}}]^\top \in [0, 1]$. The term $x_{\text{subj}} u_{\text{stimulus}}$ in (3a) simplifies the Basson model, as discussed in Section 1.1, such that as soon as the subjective arousal is positive, positive erotic stimuli will lead to increased physiological arousal. Moreover, this equation models that higher subjective arousal and/or more intense sexual stimuli lead to a faster increase in physiological arousal. The intuition captured in $x_{\text{phys}} u_{\text{pressure}}$ in (3b) is then that during physiological aroused conditions, applying vaginal pressure induces pleasurable sensations. Finally, subjective arousal is modeled to potentially increase independently due to a feeling of pleasure and/or erotic stimuli. This is captured by the two separate terms x_{pleasure} and u_{stimulus} in (3c). As in the COF, all equations in the COP include a term on the right-hand side to ensure the origin is an asymptotically stable attractor so that all state variables tend to zero in the absence of external stimuli.

The subjective pleasure measurement is considered to be measured directly such that

$$y_{\text{pleasure}} = x_{\text{pleasure}} \,. \tag{4}$$

3.2 A note on the identifiability issues of the COF and COP models

Jackson et al. (2024) discuss the structural and practical identifiability issues of the COF model, which were overcome by determining the identifiable parameters using subset selection. Although the results of subset selection were not included for the COP model, since the pleasure measurements are subjective and sparse, a subset selection for determining the practically identifiable parameters from the data resulted in a highly ill-posed problem. There is, thus, a need to include the influence of subjective pleasure on the COF without performing parameter identification on the COP in (3).

3.3 Including the influence of pleasure by means of a Switched System

We instead propose a new method for including the influence of pleasure on the COF by drawing on the ideas presented in Knorn et al. (2018). We can see from the pleasure measurements in Figure 1 that subjective pleasure exhibits four types of behavior:

- continuation (0), where $\dot{y}_{\text{pleasure}} \approx 0$;
- positive jump (+), where $\dot{y}_{\text{pleasure}} > 0$;
- negative jump (−), where $\dot{y}_{\text{pleasure}} < 0$; and
- stop (−∞), where $\dot{y}_{\text{pleasure}} \approx -\infty$

In Knorn et al. (2018), these discrete states were used to identify a region $(u_{\text{pressure}}, \dot{u}_{\text{pressure}}, u_{\text{volume}}, u_{\text{stimulus}}) \in Q_i$ for $i \in \{0, +, -, -\infty\}$ such that we can describe the transitions between the states by the system in Figure 4.

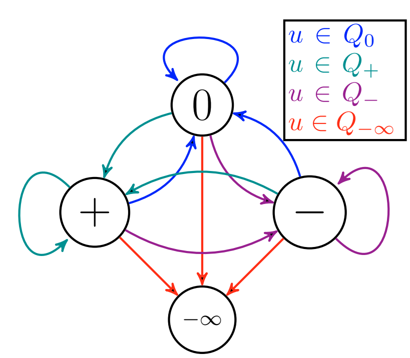


Figure 4. The switched system of transitions between constant (0), increasing (+), and decreasing (−) pleasure; and unpleasurable events (−∞).

We thus use the methods explained in Jackson et al. (2024) for dealing with online and offline measurement data; due to the sparsity of the stop measurements; as a weighted least squares problem and identify the parameters of the COF in (1)–(2) for each of the states of the switched system where we obtain separate models COF_i for $i \in \{0, +, -\}$ dependant on the patient pleasure levels. We note that we are unable to estimate the parameters for state $-\infty$ due to the experiments ending after the stop button is pushed.

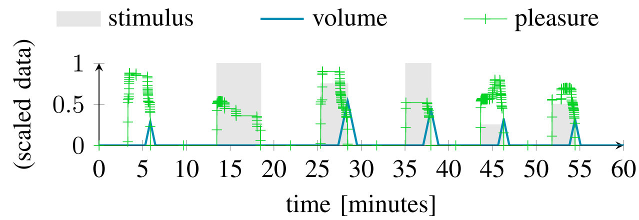
4. RESULTS AND DISCUSSION

This section presents the results of using the switched system to identify the separate models COF_i for $i \in \{0, +, -, -\infty\}$ compared to a black-box and grey-box modeling approach presented in Jackson et al. (2024). The patient data was segmented by film and randomly split into an 80–20 identification-validation set. Data segments were then extracted based on the state of the pleasure, i.e., increasing, decreasing, constant, or stopped. Weighted least squares approach was adopted for parameter identification to deal with the online and offline data to estimate the identifiable parameters in (1)–(2), i.e., θ_2, θ_5, θ_6, θ_8, θ_9, θ_{11}, where the unidentifiable parameters were set to the specified values $\theta_1 = 0.35$, $\theta_3 = 3$, $\theta_4 = 0.75$, $\theta_7 = 0.5$, $\theta_{10} = 0.75$. The fixed values were chosen heuristically, and the parameter search space was determined using a Latin hypercube sampling method.

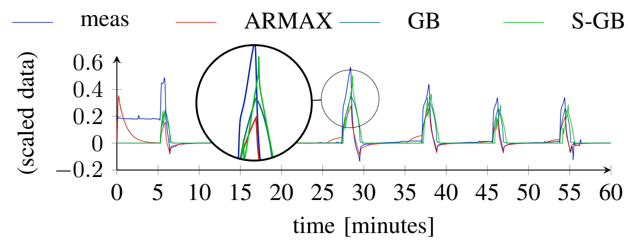
In Table 1, we present the results as a comparison against previously established black-box and grey-box models and visually plot a comparison of the different models for a random example data-set in Figure 5. We can see in Table 1 that the fit values for the switched model have high variance. However, we can also see from the plots in Figure 5 that visually, the fits seem to follow the trend in the pressure and stop data better than the black-box and grey-box models. It is also evident from these plots that there is a slight time delay in the switched model. This phenomenon is likely due to the subjective pleasure measurements being taken with some delay since the participants are only prompted to provide this measurement every 20 seconds and sometimes the value is left unreported. We additionally note the effect of the visual stimulus on the results. During the data processing, we assumed that the high-arousal sexual stimulus would elicit a higher sexual response and hence attributed it with a value of 1 for the visual stimulus. Likewise, we assumed the low-arousal sexual film, the high-arousal non-sexual film, and the low-arousal nonsexual film to decrease in their effect and assigned the values 0.75, 0.5, and 0.25 to them, respectively. The neutral stimulus was assigned a value of 0. Although the assumption that the different films have different levels of stimulation is likely sound, this assumption has not been validated and the variability in the effect of the different stimuli could be overly exaggerated by this assumption.

Table 1. Predictive capabilities of the different models. Values are fit values (mean ± standard deviation), i.e., fit $= 100\left(1 - \frac{\|Y - Y_M\|_2}{\|Y - \bar{Y}\|_2}\right)$, where Y is the validation data, Y_M is the predicated value using the model, $\|\cdot\|_2$ is the $\mathcal{L}_2$-norm and $\bar{Y}$ is the mean value of the validation data.

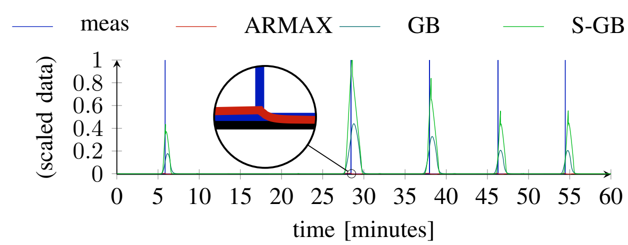
Model	Pressure Fit	Stop Fit
ARMAX	44.68 ± 17.63	0.2691 ± 0.0575
Grey-box online-offline	28.41 ± 12.29	7.291 ± 4.689
Switched model	20.75 ± 19.66	8.044 ± 3.58



(a) Measured input data including the VPI volume, erotic/sexual stimulus, and patient subjective pleasure ratings.



(b) Measured VPI pressure (meas) compared with the three models: ARMAX, grey-box (GB), and switched grey-box (S-GB) with fit=21.9.



(c) The measured patient stop events (meas) compared with the three models: ARMAX, grey-box (GB), and switched grey-box with fit=17.6

Figure 5. Plot of how the different patient models perform on a random dataset.

5. CONCLUSION

In this paper, we proposed a way to model the impact of pleasure on pain and fear characteristics during vaginal dilation exercises. The proposed switched system overcomes the standard problems of structural and practical identifiability. The method moreover uses a weighted least squares approach to deal with the sparsity of the stopping events and to avoid biasing trends in the model.

The results indicate that the model does not perform as well as the grey-box model where the impact of pleasure was ignored, but through visual inspection of the results, the model demonstrates a promising way of dealing with the dynamics that the original grey-box model failed to capture. The results are still, however, highly variable. The variability is likely due to the integration of subjective measurements which vary greatly given the individual and pose a time-varying delay based on when patients choose to appraise their experience. Additionally, the impact of the different visual sexual stimuli should be rather considered as blind inputs where the time instances of the films are known but the impact is unknown. We further note that there are still obvious dynamics in the data that the model fails to capture which motivates the use of deep learning methods for nonlinear system identification.

Moreover, we know from the literature that a patient's psychological state affects their physical state. This prompts the inclusion of psychological observers in the form of emotional recognition from the collection of physiological signals using a smartwatch device. As discussed in Mattern et al. (2023), however, this is a highly personalized problem and is highly dependent on sensor placement and daily form. Further, Mattern et al. (2023) questions the validation methods used in the current state-of-the-art emotion recognition methods. Thus, we do not include the collection of physiological signals for the purpose of emotion recognition in this study.

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