Real-Time Visualisation and Analysis of Internal Examinations – Seeing the Unseen

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Abstract. Internal examinations such as Digital Rectal Examination (DRE) and bimanual Vaginal Examination (BVE) are routinely performed for early diagnosis of cancer and other diseases. Although they are recognised as core skills to be taught on a medical curriculum, they are difficult to learn and teach due to their unsighted nature. We present a framework that combines a visualisation and analysis tool with position and pressure sensors to enable the study of internal examinations and provision of real-time feedback. This approach is novel as it allows for real-time continuous trajectory and pressure data to be obtained for the complete examination, which may be used for teaching and assessment. Experiments were conducted performing DRE and BVE on benchtop models, and BVE on Gynaecological Teaching Assistants (GTA). The results obtained suggest that the proposed methodology may provide an insight into what constitutes an adequate DRE or BVE, provide real-time feedback tools for learning and assessment, and inform haptics-based simulator design.

Keywords: Internal Examinations, Digital Rectal Examination, Bimanual Vaginal Examination, Prostate Cancer, Rectal Cancer, Vaginal Abnormalities, Cervix Abnormalities.

1 Introduction

Physical examination through Digital Rectal Examination (DRE) or bimanual Vaginal Examination (BVE) plays a key role in the early diagnosis and detection of anorectal [1,2], prostate [3], vaginal and cervix [4] abnormalities. Despite this importance, teaching and assessment of DRE and BVE is often inadequate as visual cues are minimal – both learner and trainer are unable to see what each other is doing. The intimate nature of these examinations results in patients being unwilling to be examined by junior trainees.

In addition, there is a lack of understanding of what are the pressure and palpation techniques that lead to an adequate examination. Previous attempts have focused on computing performance metrics from pressure sensors embedded on an instrumented

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prostate [5,6], or on a pelvic benchtop model [7]. The main objective of such studies has been the validation of the proposed simulator by comparing the performance of experts and novices. However, by using a discrete number of sensors on fixed anatomical locations, the proposed systems not only fail to capture other important regions such as the rectum and vaginal walls, but are also unable to offer a continuous pressure map across the anatomy to be examined, which may help better understand how to properly conduct a DRE or BVE.

In this paper we describe a framework that is able to continuously capture real-time pressure and position information during a DRE or BVE, playback an examination, as well as provide tools for the analysis of pressure and palpation techniques. Using a previously published Cognitive Task Analysis (CTA) that decomposes the examination into a series of steps or tasks [8,9], we have annotated these steps with a range of properties computed from the sensor data. Our hypothesis is that our system will enable better understanding and assessment of DRE and BVE by quantifying and analysing trajectories and forces. First, the sensor setup, 3D visualisation, task decomposition, task properties and experimental studies are described. Results of the three studies for DRE and BVE are then presented, followed by a discussion and conclusions.

2 Methods

2.1 Position Tracking and Pressure Sensing

A position sensor coil (Aurora Micro 6DOF 0.8mmx9mm) was placed on the nail of the expert's examining finger(s) and tracked with an electromagnetic tracker (NDI Aurora, tracking volume 50x50x50mm) located next to the DRE / BVE benchtop model or Gynaecological Teaching Assistant (GTA). A capacitive pressure sensor pad (Pressure Profile System FingerTPS) located on the fingerprint was used to capture pressure during the examination (Fig. 1). Both Application Programming Interfaces (APIs) from NDI and PPS were integrated into a single-thread-based application using Qt and libQGLViewer, capturing each examination at a 40Hz sampling rate. This configuration allows for continuous data recording (position, orientation and pressure) while palpating any internal structure during the examination.

Fig. 1. a) DRE: a Micro 6DOF position sensor coil on the nail of the index finger with a capacitive pressure sensor next to it. b) BVE on GTAs: a consultant wearing position sensors (index and middle fingers of both hands) with five pressure sensor sheaths (one additional next to middle finger of external hand).

2.2 3D Visualisation

The DRE and BVE benchtop models were CT scanned to produce reference anatomical models to be used during the visualisation. 3D surface models were constructed using marching cubes in VTK. Before performing the examination, four anatomical landmarks were touched by the expert using one of the tracked index fingers. These landmarks were used to register the 3D surface models with the corresponding benchtop model using the standard Iterative Closest Point (ICP) algorithm in VTK (Fig. 2).

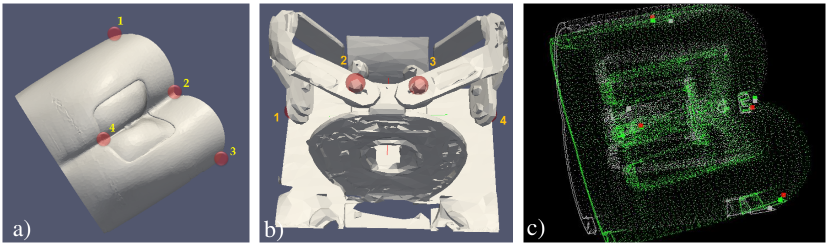


Fig. 2. 3D Surface models and landmarks of a) DRE and b) BVE benchtop models in VTK; c) Results of ICP landmark-based registration of DRE model are shown in green (mesh before registration in grey and landmarks from sensors in red).

Our framework allows real-time visualisation during recording, as well as retrospective playback of a DRE or BVE. 3D DRE models of a specific prostate type (N – normal, UB – unilateral benign, BB – bilateral benign, UC – unilateral carcinoma, BC – bilateral carcinoma) or 3D BVE models may be loaded and registered. A 3D mesh representation of the examining finger is shown for visual purposes only and it is translated and rotated according to the position sensor, as well as colour-coded to indicate the amount of pressure recorded by the relevant pressure sensor at that particular anatomical location. A real-time pressure plot indicates the applied pressure at each time point (Fig. 3).

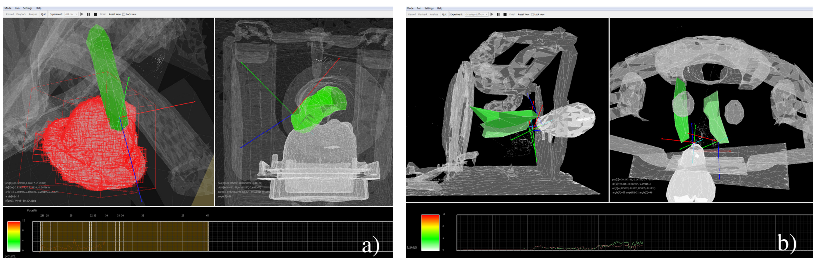


Fig. 3. a) DRE with a unilateral carcinoma prostate (left - prostate with collision detection tree). b) BVE model with a position sensor embedded in the movable uterus, index and middle fingers.

2.3 Task Decomposition and Annotation

During playback, the pressure plot is used to label/annotate all relevant steps pertaining to the internal stage of DRE and BVE (Table 1) by selecting the initial and finishing time intervals of each task. These labels were then used to compute a series of properties (see section 2.4): duration, anatomical coverage, finger(s) orientation, and palpation primitives. The annotated tasks form the cornerstone of our data analysis.

Table 1. *Left*: physical and sensorial tasks for the internal examination stage during DRE [8]. *Right*: palpation and discrete finger movement examination tasks for BVE [9].

Task	DRE task
23	Position pad of right index finger on anus
24	Apply gentle pressure with finger pad on anus for a few seconds
26	Insert finger with pad posteriorly
27	Assessment of sphincter tone
28	Insert finger beyond sphincter into rectum
29	Coccyx is reached
32	Rectal wall palpation: start circumferential palpation at level of coccyx
33	Rectal wall palpation: systematic, full 360 degree sweep
34	Prostate palpation
45	Remove finger

Task	BVE task (discrete sections)
4	Insertion of fingers
5	Examination of the cervix
6	Test for cervical excitation
7	Examination of the uterus
8	Palpation of adnexae
9	Uterosacral ligaments
10	Closing

2.4 Task Properties

For simplicity and due to space constraints, we only describe the properties obtained for the DRE tasks as an example of the type of properties that may be generated with our framework. Using Dickinson's subdivision of the prostate [10], together with position tracking data of a 7mm-radius sphere representation of the fingertip (centre located 7mm under the nail) and a collision detection algorithm based on an Axis Aligned Bounding Box (AABB) tree representation of the prostate, it is possible to label each triangle of the 3D mesh during playback as it is palpated, according to the region to which it belongs. Each region was assigned a state (normal, enlarged or carcinoma) according to the type of prostate being examined and its location. Quaternion information captured from position sensors was transformed into a single scalar representing finger orientation [-90,90] during palpation by computing the cross product of the tangent of the sensor data to the normal of the triangle (see Fig. 4).

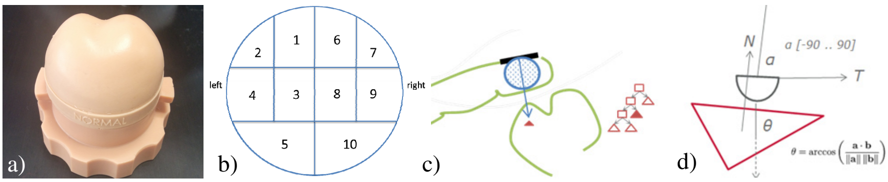
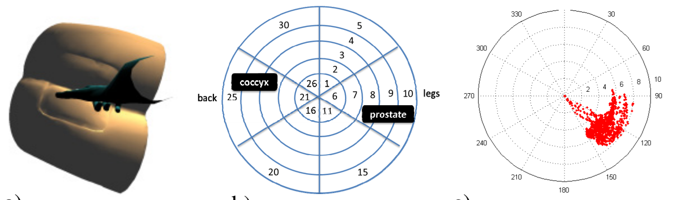


Fig. 4. a) DRE benchtop model (normal prostate). b) Region labelling. c) Collision detection between finger and prostate. d) Finger orientation obtained during collision detection based on the normal of colliding triangles and tangent vectors computed from sensor quaternion data.

The rectum was subdivided in a similar way based on finger orientation and insertion depth, with location data represented in polar coordinates (Fig. 5).

Palpation primitives refer to the fundamental elements of finger movement. They include: a) abduction/adduction, b) flexion/extension, c) supination/pronation and d) compliance. These primitives describe tasks during internal examination [8,9] and are inferred from position data. By computing the frequency of occurrence of palpation primitives (rectum and prostate), we expect to correlate frequencies with examination styles across models and experts (Table 2).



a) b) c)

Fig. 5. Subdivision of the rectum: a) DRE benchtop model with a finger pointing downwards (180°) just before insertion (0cm). b) 30 regions defined in polar coordinates based on finger orientation (sectors subdivision every 60°) and insertion depth (concentric rings every 2cm). c) An example of an examination performed by a urologist.

Table 2. Computing frequency of palpation primitives for the prostate (abduction/adduction, flexion/extension, compliance) and for the rectum (supination/pronation and compliance)

	Definition	**Frequency**
Abduction/Adduction	Lateral movement between adjacent regions (Fig. 4b)	On occurrence while palpating adjacent regions
Flexion/Extension	Upward and downward movement between adjacent regions belonging to the base (1,2,6,7), mid (3,4,8,9) and apex (5,10) sections of the prostate	On occurrence while palpating adjacent regions
Supination/Pronation	Movement relative to the orientation of the finger/hand	When the hand is rotated ± 45° (Fig. 5b)
Compliance	Movement related to the exertion of forces in a single region	When the standardised pressure is ≥1 standard deviation of applied pressure

2.5 Experimental Studies

Three different experimental studies (Table 3) were designed to develop and validate the use of our visualisation and analysis tool: a) DRE on a benchtop model, b) BVE on a benchtop model and c) BVE on GTAs (Fig. 6). Ethics approval was obtained from the NHS National Patient Safety Agency Research Ethics Committee.

The aim of the first study (DRE on benchtop model) was to establish an adequate sensor calibration protocol, validate the registration process, and assess the quality of the recorded data. It also allowed us to integrate the annotation of CTA-based tasks, validate the collision model of the prostate and devise an analysis pipeline. The purpose of the second study (BVE on benchtop model) was to extend our framework to

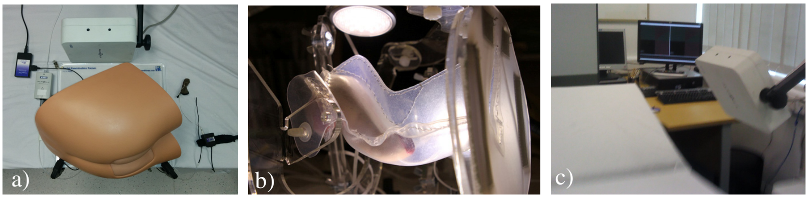


Fig. 6. Experimental setup. a) DRE benchtop model. b) Internal view of bespoke BVE benchtop model. c) BVE on GTAs.

Table 3. Description of experimental studies

	DRE benchtop	BVE benchtop	BVE on GTAs
Subjects	N, UB, BB, UC, BC[1]	Movable uterus and ovaries	4 GTAs
Participants	1 colorectal consultant	10 gynaecology consultants	2 gynaecology consultants
Examinations	2 per subject	2 per subject	1 per subject
Total	10	20	8
Position sensors	internal (1)	internal (2)	internal (2)
		uterus (1)	external (2)
Pressure sensors	internal (1)	internal (2)	internal (2)
			external (3)

[1] Prostate types: normal (N), unilateral benign (UB), bilateral benign (BB), unilateral carcinoma (UC), bilateral carcinoma (BC)

multiple position and pressure sensors, including a position sensor to track the movement of the uterus. The intention of the third study (BVE on GTAs) was to pilot the use of our framework on real subjects.

3 Results

In order to compare pressure across experiments, the pressure data was normalised using a sample version of the Z-score to compute an estimate for the number of standard deviations a given pressure is from the mean. IBM SPSS Statistics was used to obtain descriptive statistics and run univariate ANOVA tests.

3.1 DRE on a Benchtop Model

Regarding pressure, we found no significant differences between the average standardised pressures applied to normal, enlarged or carcinoma regions across prostates. A significant difference ($p<.01$) was found between the average standardised pressure applied to normal (μ=-0.03) and carcinoma (μ=0.48) regions of the UC prostate type.

When comparing across tasks (Table 1), task 34 (prostate palpation) exhibited the highest average standardised pressure as well as the largest variability (μ=0.52, σ= 0.81). Large variability was also observed during task 33 (rectum palpation – μ=-0.78, σ=0.57), task 26 (finger insertion – μ=-0.55, σ=0.59) and task 45 (finger removal – μ=-0.64, σ=0.62). In terms of average duration, task 34 took twice as long as task 33, with an average 60% of the prostate being palpated against only 35% of the rectum.

With respect to movement primitives during prostate palpation (Table 2), on average, abduction/adduction and compliance were done the most in the BC prostate (10 and 3 times, respectively), whilst flexion/extension was done the most in BB and UC prostates (8 times). Related to the rectum, we studied movement primitives for the whole examination based on polar coordinates (Fig. 5b). On average, supination was performed the most during UB examinations (19.5 times), whilst compliance was performed the most during UB and UC examinations (5.5 and 4.5 times respectively).

3.2 BVE on a Benchtop Model

The use of multiple sensors allowed us to study the behaviour of the fingers, as well as the movement of the uterus during the examination. On average, the distance between the position tracking sensors of the internal examining fingers was the closest during task 7 (palpating the uterus – 32.37mm), with a slight increase during task 5 (palpating the cervix – 37mm) and task 8 (palpating the adnexae – 38.98mm). The smallest average distance between the sensor in the uterus and the sensor in the index finger was during task 7 (μ=33.38mm) followed by task 5 (μ=35.11mm).

Regarding the movement of the uterus, the sensor in the uterus moved on average the most during task 5 within a distance of 23.73mm (pull/push), 26.51mm (upward/downward) and 19.14mm (sideways), whilst it moved in a reduced space during task 7 within an average distance of 18.6mm, 22.3mm and 16.33mm, respectively. Considering the initial position of the sensor in the uterus, the uterus was pushed a maximum distance of 27.16mm and lifted a maximum distance of 10.43mm during task 5, compared to 26.72mm and 12.44mm during task 7.

3.3 BVE on GTAs

We studied the behaviour of the fingers of both hands and the pressure applied during examination of real subjects. The average distance between the sensors on the external fingers (index and middle) during task 5 was 24.8mm, whilst the average distance between the sensors on the internal fingers was 49.6mm, and between the sensors on the index fingers of both hands was 159.1mm. During task 7, we observed that the palpation of the uterus was occasionally performed with one finger. When two fingers were used, the minimum distance was 22.96mm. The external average distance was 22.6mm, whilst the average distance between the hands was 116.3mm. During task 8, the average distances were 22.27mm, 36.59mm and 94.76mm.

Regarding pressure, the average standardised pressure measured by the sensors on the ring, middle and index fingers of the external hand during task 5 was -0.73, -0.64, -0.59, whilst the standardised pressure recorded on the index and middle fingers of the examining hand was, on average, -0.18 and -0.14. During task 7, the average standardised pressures were 0.53, 0.24, 0.31 for the external hand, and 0.16 and -0.18 for the examining hand. During task 8, the average standardised pressures were 0.72, 0.82, 0.63 for the external hand, and 0.66 and 0.87 for the examining hand. A significant difference ($p<.01$) was found between the averages of these five pressure sensors during task 5 (μ=-0.46), task 7 (μ=0.21) and task 8 (μ=0.74).

4 Discussion and Conclusions

We have developed a framework for visualisation and analysis of internal examinations through real-time continuous position and pressure sensor data. Findings from three studies confirm our hypothesis of enabling better understanding and assessment of DRE and BVE by unveiling the unseen through playback and analysis of task-based information that includes quantitative measures such as pressure, duration, finger position and orientation, and movement primitives.

DRE on a benchtop model – the fact that a significant difference was only found between the average pressure applied to normal and carcinoma regions of the UC prostate type suggests that the pressure applied to normal and enlarged regions is within a similar range. The potential of using movement primitives to better understand and analyse palpation patterns has been illustrated by the different frequency of such primitives depending on prostate type.

BVE on a benchtop model – the use of multiple sensors allows the observation and study of the behaviour of internal fingers during the examination, as well as movement of the uterus. Coordinated bimanual interaction when lifting the uterus resulted in a small distance between fingers and between fingers and the uterus. Also, during palpation of adnexae, the internal fingers appear to slightly separate in order to lift the adnexae and be able to palpate them externally. Results also suggest that the uterus is not only lifted, but also pushed during bimanual interaction.

BVE on GTAs – a similar behaviour of internal and external fingers was observed on real subjects, together with a reduction in the distance between hands for tasks 5, 7 and 8 (larger to smaller). Average standardised pressure was significantly different across these tasks, with the highest pressure applied during adnexae palpation. This variation in pressure applied and finger behaviour suggests that different palpation patterns are used when examining the uterus, cervix and adnexae.

Compared to other studies, our approach allows us to understand pressure applied to specific organs continuously, as well as the movement of examining fingers throughout the examination. There is significant potential for our framework to be used as a teaching and learning tool for unsighted examinations, offering trainees detailed feedback, allowing them to see what the trainers are doing, and allowing the trainers to objectively assess performance during a DRE or BVE.

Future work includes recruiting more participants from specialities that typically conduct DRE in order to investigate differences in performance and emphasis. A study on human subjects (Rectal Teaching Assistance) will follow. Further studies using a linear progression model will allow us to correlate quantitative task properties with adequate and competent performance for both DRE and BVE.

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