Enhancing Breast Palpation Training with a Dynamic Multilocation Particle Jamming Interface

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Abstract. Breast cancer is the most commonly diagnosed malignancy amongst women worldwide, accounting for approximately 670,000 deaths in 2022. While physical examination is a vital tool for early detection, effective training remains a challenge. This work demonstrates a dynamic softness-changing tactile display capable of rendering lumps in variable locations to support manual breast examination training.
The system uses particle jamming and load-based tactile sensing to create differential stiffness across a monolithic display, while resistive heat pads provide thermal indications of infection. A 3D visualisation adds clinical context. We evaluated the system with 14 doctors and medical students. Participants correctly identified lump locations in 66% of cases and elevated temperatures in 88% of cases. Notably, qualified doctors demonstrated 22% higher accuracy than novices. These results validate the system's ability to distinguish expert from novice performance, suggesting it is a viable tool for objective clinical skills assessment and training.

Keywords: Soft haptics · Thermal haptics · Medical simulation

1 Introduction

Breast cancer is the most commonly diagnosed malignancy among women worldwide. In 2022, an estimated 2.3 million women were diagnosed with breast cancer, with approximately 670,000 associated deaths globally [9]. Through clinical breast examination (CBE), clinicians manually assess a range of tissue characteristics, including hardness, mobility and temperature. Malignant breast lesions typically present as firm, irregular, and immobile masses. Benign conditions such as lipomas usually manifest as soft, while infective pathologies such as abscesses are characterised by localised swelling and increased temperature. Accurate differentiation between these conditions relies heavily on tactile perception and clinical experience. Ensuring that medical students and trainee clinicians are proficient in CBE is essential to making rapid and accurate diagnoses. However, the limited availability of repeatable, and low-stakes training opportunities underscores the need for better haptic medical simulators.

Research on medical simulation places great emphasis on multisensory systems that combine visual feedback including XR and screen-based platforms, with haptic feedback. Robots enabling interactive force feedback have been widely used in medical simulators, particularly in gynaecology [11], orthopaedics [10], and palpation [15, 7]. However, while the inclusion of physical handles is appropriate in tool-mediated procedures such as orthopaedics, this paradigm introduces limitations for dexterous skills [15, 11]. In such contexts, tactile cues including tissue drag, and manual skill practice are degraded or lost.

In soft robotics, jamming refers to the ability of granular materials to change their stiffness when compressed [8]. Jamming actuation provides reversible, tunable stiffness by vacuum-controlling granular, laminar, or fibrous media, with examples summarized in a recent review [5]. Early applications to haptics introduced programmable-stiffness devices and sensing for malleable user interfaces, leading to tactile displays well-suited to palpation training [6, 14]. Wearable implementations provide kinaesthetic feedback in glove and full-body garments for interactive use [13, 1]. Interactive deformable surfaces and hybrid approaches extend expressivity by coupling jamming with vibration to add tactile cues [3]. Pump-free actuation broadens form factors and responsiveness, while particle jamming actuators have shown clinically relevant stiffness feedback for palpation tasks [2].

This work extends these developments to propose a dynamic, multilocation particle jamming interface applied to breast palpation training, emphasizing controllable stiffness, regional heterogeneity, and an additional thermal cue.

2 Breast exam simulator

This section presents a breast examination simulator in which a localised region of increased hardness was dynamically rendered in response to finger palpation. The simulator also incorporated localised thermal feedback and real-time visualisation to simulate realistic breast examination.

2.1 Interactive lump formation

The interactive lump formation system dynamically modulates the hardness of the surface in response to the position of the user's hand or finger. The approach combines load-based finger tracking with a rapidly adjustable particle jamming interface, allowing the apparent rendering of a localized, hard lump on an otherwise soft surface.

The position of the finger is estimated using four load cells mounted below the device. When the user presses on the surface, each load cell measures a normal force. The calculation of the total applied force and the current position of the finger uses the same principles and equations as those presented in [12].

A predefined lump region is mapped onto the surface to represent the location of the simulated lump. This region is defined as a circular area centered at (x_0, y_0) with radius r. When the user's finger enters this region, the system uss a hardness-changing mechanism implemented using constrictive particle jamming [2], such that a hard mass appeared to be slightly buried under the surface, a similar effect to [4]. This interaction is illustrated in Fig. 1 (A).

To determine whether the hand or finger is within the lump region, the Euclidean distance between the current position and the lump centre is computed. When this distance falls below a predefined threshold corresponding to the boundary of the lump, the jamming system is activated, stiffening the surface. As the finger leaves the lump region, the jamming is released and the surface returns to its soft state.

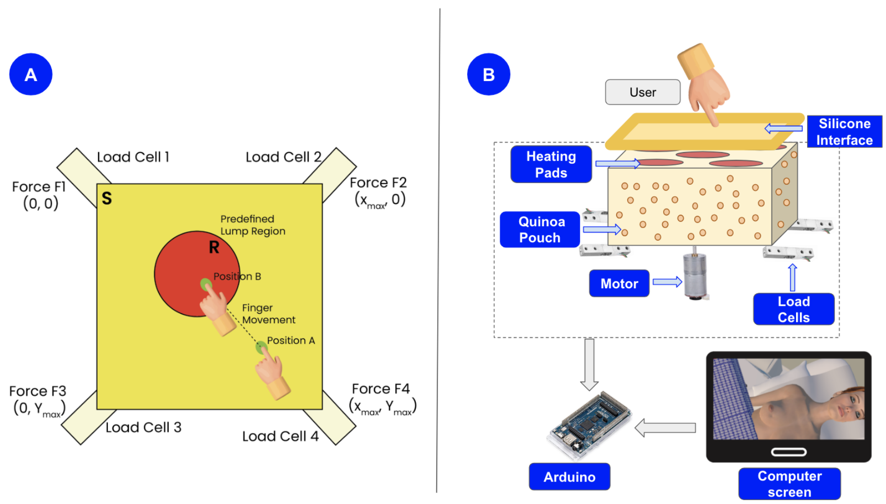

Fig. 1. A Graphical representation of the lump-forming algorithm (A) and the diagram of the prototype (B)

2.2 Temperature

To simulate a warm, infective lump, 5 polyimide resistive heating pads (8W, 50mm diameter) were attached underneath the top of the jamming pouch. A 10 kΩ Amphenol Thermistor was glued under each heating pad. Silicone (EcoFlex 00-50) was then cast around it to hold it together and give a more skin-like surface texture.

2.3 3D graphics

The 3D simulation module was developed using Unity 2022.2 LTS to provide a high-fidelity visual and auditory feedback environment for the breast palpation simulator.

Upon initialisation, the user selects a specific clinical case (e.g., a carcinoma). The system then retrieves predefined physical parameters, including stiffness (hardness) and localised temperature, and assigns randomised spatial coordinates for the lump within the virtual breast model. These parameters are synchronised with the hardware actuators to align the physical sensations with the digital environment.

During the palpation procedure, the hardware continuously reports contact pressure and 2D coordinates back to the PC application. To simulate realistic tissue behaviour, a mesh vertex displacement algorithm was implemented. As the user applies pressure, Unity calculates the depth and spatial range of the deformation in real-time. This dynamic update ensures that the visual compression of the virtual skin accurately reflects the tactile feedback perceived by the user's fingertips.

To support the pedagogic effectiveness of the simulator, an integrated assessment follows the interactive session. Users are asked to identify the lump type based on the haptic cues (stiffness and thermal differences) they experienced in a multiple-choice quiz.

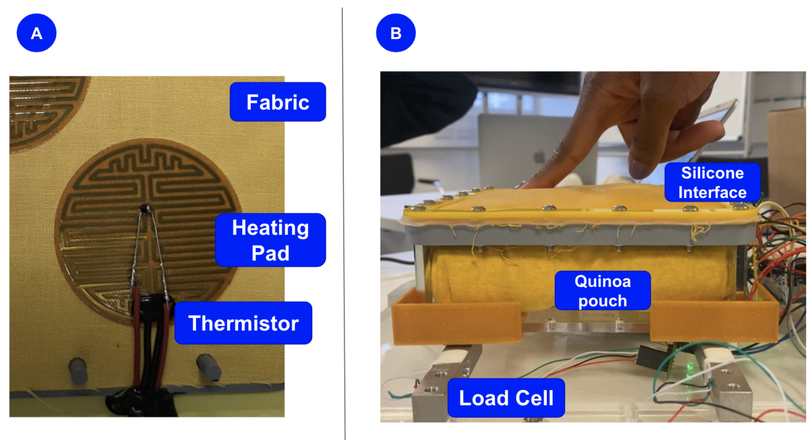

Fig. 2. The setup of the thermistors on the heatpads before silicone is poured (A) and the prototype breast palpation simulator (B).

2.4 Performance and characterisation

Performance was evaluated in terms of being able to achieve clinically-relevant hardness, finger-tracking accuracy, temperature stability, and residual heat dissipation time.

Interface surface hardness was measured as a function of motor rotation angle at the centre of the interface using a Shore A durometer across the full range of movement, as in [2]. The hardness value at each angle was calculated as the average of three measurements. The heating pads were concealed with silicone and resulted in a higher minimum hardness at 0° (15A) compared with the fabric-only surface (3–5A). The maximum achievable hardness was approximately 23 A for the silicone–heating pad configuration. Hardness was spatially uniform across the interface in both the normal skin and maximal hardness states, and results were repeatable across measurements.

Finger-tracking accuracy was evaluated by dividing the interface into a 5×5 grid, with each square measuring 3×3 cm, and computing the difference between the real finger location and the algorithm output. Localisation accuracy was quantified using the mean Euclidean error between measured and real positions which was 47.39 mm.

Temperature performance was assessed using a thermal camera (FLIR TG267) and demonstrated high repeatability across trials (±0.2 °C). Residual heat dissipated completely within approximately 2–3 minutes.

3 Experimental validation

The system's clinical relevance was evaluated through a user study.

3.1 Participants

14 doctors and medical students were recruited to evaluate the simulation. Of these, 6 were qualified doctors with a range of surgical specialisms and experience levels, and 8 were medical students in years 2-6 of a 6-year course. All user studies were conducted in accordance with Imperial College London's guidelines for research involving human subjects and the Declaration of Helsinki. The study received a favourable ethical opinion from the Imperial College Department of Surgery and Cancer and the Science, Engineering and Technology Research Ethics Committee (certificate 8138766). All participants gave written informed consent before beginning the study.

3.2 Experiment setup

Participants were seated in a quiet room facing the touchpad and computer display, as shown in Fig. 2. Noise-cancelling headphones were worn to mask the sound of the motor during actuation while still allowing participants to communicate with the investigators.

3.3 Protocol

After consenting, participants received an induction to the simulator from a qualified doctor with clinical teaching experience. Participants were then presented with a series of simulations, consisting of an abscess, carcinoma, lipoma, and normal skin (control/no lump). Each lump could appear in any of the left or right, upper or lower quadrants, or the centre of the simulator. The ordering of the presentations and location of each were randomised.

Following each presentation, participants reported the clinical characteristics of the lump and proposed a diagnosis from a multiple choice list, which also included fibroadenoma which were never presented.

4 Results

The results of the evaluation study are shown below.

4.1 Lump location & temperature

The highest identification accuracy was observed when the lump was not present with 86% of participants identifying this, then for the Centre, LLQ (left lower quadrant) and RUQ regions, with 78%, 66% and 64% of correct predictions, respectively. Misidentification was most frequent for LUQ (43%), where responses were distributed across adjacent regions. Figure 3 presents the confusion matrix of participant responses for lump localisation across six anatomical regions.

Heat detection performance showed 10 true positives and 39 true negatives, with 3 false positives (5%) and 4 false negatives (7%), corresponding to an overall accuracy of 88%.

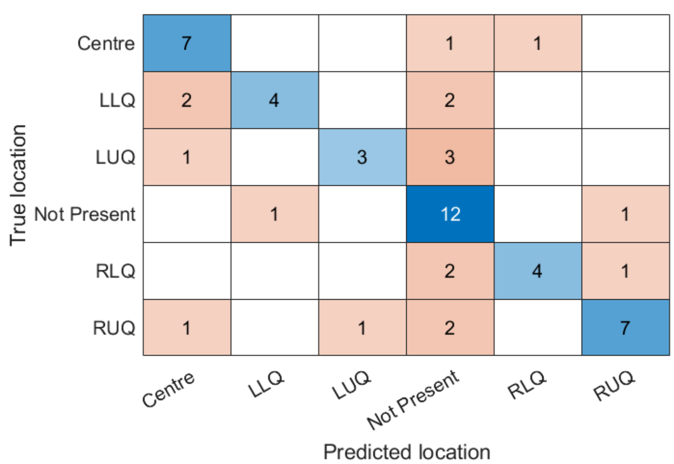

Fig. 3. Confusion matrices showing response rates from participants when asked about the possible diagnosis of a breast lump

4.2 Clinician validation & Student evaluation

Participants were asked to suggest a diagnosis for each lump based on its physical characteristics. In the clinician cohort (Fig.4-A), correct identifications were highest for normal skin (83%) and abscess (80%), followed by carcinoma (67%) and lipoma (60%). Misidentifications were primarily observed between carcinoma and lipoma. In the student cohort (Fig.4-B), correct identifications were highest for normal skin (88%) and abscess (88%), followed by carcinoma (38%) and lipoma (33%). Lipoma exhibited the highest misidentifications rate, with five cases predicted as normal skin. Carcinoma cases were evenly misidentified across all the available conditions. Overall, both groups show higher diagnostic performance for normal skin and abscess compared to carcinoma and lipoma and clinicians outperformed students, achieving a higher diagnostic accuracy by approximately 22%.

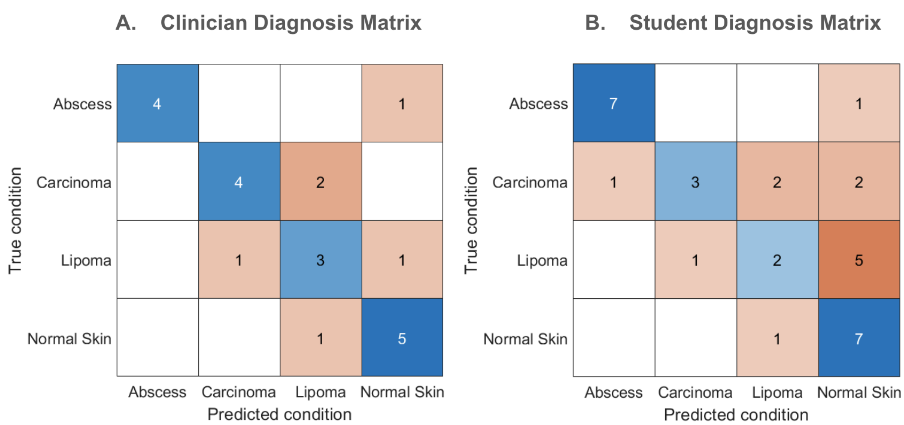

Fig. 4. Confusion matrices showing correct response rates from clinicians (A) and students (B) when asked about the possible diagnosis of a breast lump

5 Discussion

A majority of participants could accurately detect heat when present (88%). 5% of the participants wrongly detected heat when the feature was not enabled. This small portion of false-positive detections may be attributed to residual heating from the heating pad between successive case presentations.

Participants were also able to accurately identify the location of the lumps in 66% of the cases. Instances of wrong localisation may be explained by participants exploring the breast too quickly for the response rate of the controller, which would have introduced a delay between contact and full hardness-change, thereby reducing spatial precision.

With respect to diagnosis, both clinicians and students were able to accurately identify abscess and normal skin states as seen in figure 4. This suggests that the heating pads were not identified as palpable lumps during examination. The high diagnostic accuracy for abscesses is likely due to the introduction of heat, which distinguished this condition from other lump types that do not raise skin temperature. Given the high rate of correct heat detection, this thermal cue appears to have been particularly salient to participants.

In contrast, carcinoma and lipoma were considerably more difficult to distinguish for both clinicians and students. This is likely because the primary differentiating feature between these two conditions was tissue hardness. The hardness range achievable by the prototype didn't meet the very hard consistency typically associated with carcinoma, resulting in carcinoma presenting too softly. This highlights a key limitation of the current simulation. Moreover, carcinomas are typically embedded deeper within tissue rather than located superficially, a characteristic that could not be replicated with the device. Consequently, the lack of depth variation represents an additional limitation of the prototype for deep lumps.

Finally, clinicians outperformed students in diagnostic accuracy, which is consistent with their greater clinical experience and more developed palpation skills.

5.1 Future work

Future work on the device includes using different force thresholds to render lumps at different depths under the skin. Faster load amplifiers can improve response time and make finger tracking more accurate, improving location accuracy. Additionally, using a VR headset to conceal the platform from the user could create a more immersive training experience. Finally, adding different forms of feedback, such as pulse and texture would allow the device to support an even broader range of clinical conditions.

6 Conclusion

In conclusion, the prototype breast examination simulator was able to reliably simulate multiple clinically-relevant lumps in different locations on a homogeneous surface. The user study demonstrates a good level of clinical and educational relevance, and motivates further investigation into the range of pathologies that can be realistically reproduced. Over time, this technology has the potential to reduce reliance on passive lump phantoms, enabling more flexible, scalable, and cost-effective training and testing platforms for medical students.

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Disclosure of Interests. The authors have no competing interests to declare.

References

1. Al Maimani, A., Roudaut, A.: Frozen Suit: Towarda Changeable Stiffness Suit and its Application for Haptic Games. In: Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems. vol. 2017-May, pp. 2440–2448. ACM, New York, NY, USA (5 2017)
2. Brown, J., Bello, F.: Hardness Changing Tactile Displays for Simulating the Feel of Organic Tissues. Frontiers in Robotics and AI **11** (2024)
3. Brown, J.P., Farkhatdinov, I.: Soft Haptic Interface based on Vibration and Particle Jamming. In: IEEE Haptics Symposium, HAPTICS. vol. 2020-March, pp. 1–6. IEEE, Washington DC (3 2020)
4. Chen, Z., Crucianelli, L., Versace, E., Jamone, L.: Exploring Tactile Perception for Object Localization in Granular Media: A Human and Robotic Study. In: 2025 IEEE International Conference on Development and Learning (ICDL). pp. 1–6. IEEE (9 2025)
5. Fitzgerald, S.G., Delaney, G.W., Howard, D.: A Review of Jamming Actuation in Soft Robotics. Actuators **9**(4), 104 (10 2020)
6. Follmer, S., Leithinger, D., Olwal, A., Cheng, N., Ishii, H.: Jamming user interfaces: Programmable particle stiffness and sensing for malleable and shape-changing devices. UIST'12 - Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology pp. 519–528 (2012)
7. He, L., Maiolino, P., Leong, F., Lalitharatne, T.D., de Lusignan, S., Ghajari, M., Iida, F., Nanayakkara, T.: Robotic Simulators for Tissue Examination Training With Multimodal Sensory Feedback. IEEE Reviews in Biomedical Engineering **16**, 514–529 (2023)
8. van Hecke, M.: Jamming of soft particles: geometry, mechanics, scaling and isostaticity. Journal of Physics: Condensed Matter **22**(3), 033101 (1 2010)
9. Kim, J., Harper, A., McCormack, V., Sung, H., Houssami, N., Morgan, E., Mutebi, M., Garvey, G., Soerjomataram, I., Fidler-Benaoudia, M.M.: Global patterns and trends in breast cancer incidence and mortality across 185 countries. Nature Medicine pp. 1–9 (2025)
10. Racy, M., Barrow, A., Tomlinson, J., Bello, F.: Development and Validation of a Virtual Reality Haptic Femoral Nailing Simulator. Journal of Surgical Education **78**(3), 1013–1023 (5 2021)
11. dos Santos Machado, L., de Moraes, R.M.: VR-Based Simulation for the Learning of Gynaecological Examination. pp. 97–104 (2006)
12. Schmidt, A., Strohbach, M., Van Laerhoven, K., Gellersen, H.W.: Ubiquitous interaction - Using surfaces in everyday environments as pointing devices. Lecture Notes in Artificial Intelligence (Subseries of Lecture Notes in Computer Science) **2615**, 263–279 (2003)
13. Simon, T.M., Smith, R.T., Thomas, B.H.: Wearable Jamming Mitten for Virtual Environment Haptics. In: International Symposium on Wearable Computers. pp. 67–70. ACM, Washington (2014)
14. Stanley, A.A., Mayhew, D., Irwin, R., Okamura, A.M.: Integration of a Particle Jamming Tactile Display with a Cable-Driven Parallel Robot. In: Auvray, M., Duriez, C. (eds.) Haptics: Neuroscience, Devices, Modeling, and Applications, pp. 258–265. Springer Berlin Heidelberg (2014)
15. Ullrich, S., Kuhlen, T.: Haptic Palpation for Medical Simulation in Virtual Environments. Tech. rep. (2012)