vARtebrae: Medical Simulation for Spinal Mobilisation Employing Mechanical Metamaterials and Extended Reality

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CSS Concepts

- Human-centered computing → Haptic devices; Mixed / augmented reality; Information visualization; User centered design;
- Hardware → Simulation and emulation.

Keywords: Mechanical Metamaterials, Extended Reality, Medical Simulator, Visuo-Haptic Feedback, Physiotherapy Education

1. Introduction

Background

Clinical-approaches to physiotherapy education are designed to provide a flexible and practical learning environment. Currently, the common approach centers around instructor-led demonstrations followed by students mimicking the performed actions on participants—often other students.

The feedback provided in this approach is mainly verbal that is not only challenging to deliver but also difficult for students to interpret and apply effectively. This is particularly relevant when understanding how much force to apply and where to apply it.

Challenges

Reliance on Voluteers: risky learning environment, where mistakes can lead to physical injury, negatively affecting both the student and the volunteer

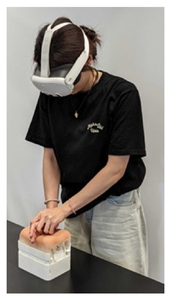
Limited Feedback: heavily rely on verbal feedback from instructors, lacking objective data on key elements like the force they apply during procedures.

Limited Scalability: A lack of a cost-effective solution that ensures equal and high-quality learning and practice opportunities for all students.

The Solution

Chacon et al. introduced SpinalLog, a TUI that offers real-time visual and passive haptic feedback via foam-based sensors, measuring user-applied force through foam deformation [1]. However, these sensors degrade over time, requiring frequent recalibration, and the simulator lacks the fidelity to replicate human back tactility.

To address this, we build on SpinalLog with two key contributions:
(1) the design and integration of mechanical **metamaterials to simulate soft tissues** in medical simulators, and
(2) an **extended reality (XR) app providing real-time 3D visual feedback** for manual motor techniques.



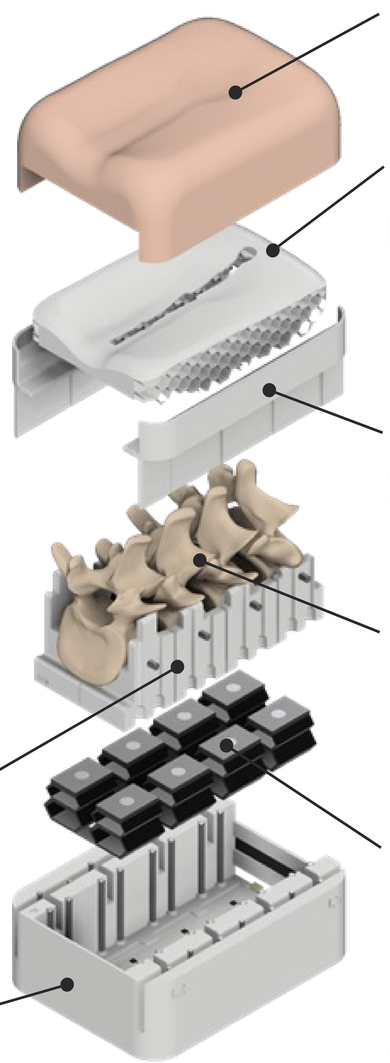
2. Design & Implementation

Approach

User-centred design approach with **physiotherapy experts**: (1) defining system requirements, (2) researching and designing prototypes, (3) iterative optimisation and refinement, and (4) conducting evaluations to enhance usability.

Mechanical Design

Emphasis on two critical factors: the physical fidelity of the spine and the palpability of its motion [1].



Silicone Cast

Emulates soft tissues like skin and fat.

Metamaterial

3D printed honeycomb structure emulating the musculature firmness.

Sliding Support

Guides and supports the vertical linear displacement of the silicone cast and Metamaterial.

Vertebrae Model

3D printed vertebrae of the lumbar spine (L2 to L5). These were identified as essential for practising spinal mobilisation techniques.

L-Shaped Supports

Keeps the bone models upright and in the right position.

Metamaterial-based Sensor Unit

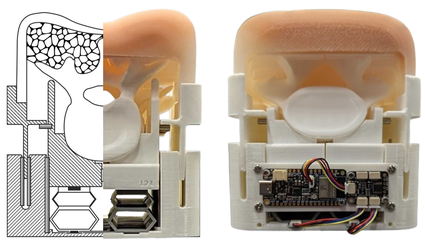
The two-level design of the unit allows for dual-level compression [2] — replicating the mechanical behaviour of the human back during spinal mobilisation.

Base

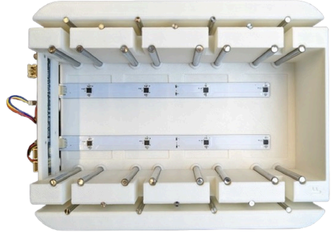
Main body of the unit that acts as the foundation for all the components.

Electronics

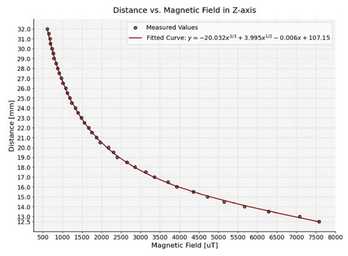
8 metamaterial-based sensors, each with a magnet on top and a magnetometer (MLX90393) in the base. ESP32 board process linear displacements based on the varying magnetic fields when sensor units are compressed.



Device Front and Back View



MLX90393 ICs Layout



Distance-Magnetic Field Graph

XR App

Passthrough Bones

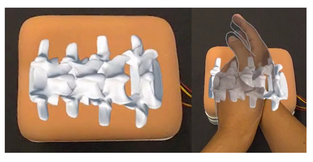
The app is designed for hand-only interaction within the virtual environment.

Unity + Meta Quest 3

Bone Activity Visualisation

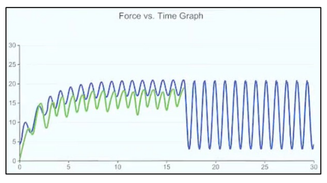
Stress on each virtual vertebra is shown in shades of red based on force magnitude.

Passthrough Bones



Overlaying virtual vertebrae allows the visualisation of their displacement and rotation during technique delivery.

Force - Time Graph



Force over time helps users visualise their performance against an expert's benchmark.

Device Calibration

Pinch interaction used to align virtual cube with the real-world device.

3. XR App Preliminary Evaluation

Early feedback from participants are summarized on 3 themes:

User experience and design: While generally well-received, some participants found the manual calibration process unintuitive, suggesting visual guides or QR-based tracking to simplify it, though most found the system easy to use once calibrated.

Anatomy visualisation: The visualization of virtual vertebrae was highly praised for demonstrating spinal movement, though some suggested adjusting rotation sensitivity for precision, with vARtebrae proving especially beneficial for novice learners.

Educational tools: The force-time graph enhanced learning by reinforcing pressure concepts, though participants suggested repositioning it and adding performance analysis tools for self-directed learning.

4. Discussion & Future Work

Visuo-Haptic Feedback: Improvements in tactile realism using mechanical metamaterials and silicone enhanced haptic accuracy, while dynamic visualizations like color-coded force cues were well-received, with suggestions to refine bone rotation sensitivity for more precise manual therapy training.

Multimodal Feedback & AI Integration: The combination of tactile and visual feedback benefits novice learners, but integrating AI-driven performance analysis and immersive training elements could enhance self-directed learning.

UI/UX: The manual calibration process was cumbersome for some users, highlighting the need for automated tracking solutions to improve setup efficiency.

Posture Guidance & Tracking: The system does not currently provide guidance on proper physiotherapy postures. Future work will explore arm and hand tracking to support students in maintaining correct technique.

Force-Displacement Calibration & Adaptability: Force estimation remains simplified, and plans include compression testing and real-time stiffness adjustment using soft robotics to create a more adaptive training experience.

System Validation & Skill Retention: Further research is needed to validate the system with physiotherapy experts and study the long-term impact of visual and haptic feedback on skill acquisition and retention.

5. References

[1] D. Antony Chacon, Eduardo Velloso, Thuong Hoang, and Katrin Wolf. 2019. SpinalLog: Visuo-Haptic Feedback in Musculoskeletal Manipulation Training. In Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '19), March 17–20, 2019, Tempe, Arizona, USA. ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3294109.3295626

[2] Alireza Mohammadi, Ying Tan, Peter Choong, and Denny Oetomo. 2021. Flexible mechanical metamaterials enabling soft tactile sensors with multiple sensitivities at multiple force sensing ranges. Scientific Reports 11, 1 (2021), 24125. https://doi.org/10.1038/s41598-021-03588-y