Characterizing External Pressure in Compression Garments Using a Modular Test Rig: Design and Initial Validation

A. Karunaratne[1a], T. Nguyen[2], D. Fletcher[3], S. Masouros[2], R.V. Loon[1] and H. Arora[1]

[1]Department of Biomedical Engineering, Swansea University, UK; [2]Department of Bioengineering, Imperial College London, London, UK; [3]Defence Materials Centre of Excellence (DMEx), Defence Science and Technology Laboratory (Dstl), UK

[a]a.karunaratne@swansea.ac.uk

Abstract. This paper presents a modular, anthropometry-aware experimental platform for characterizing the external pressure exerted by compression garments on human limb analogues. The rig incorporates swappable diameter modules spanning XS to XL (60–165 mm), magnetic silicone sleeves of variable compliance, and a multi-sensor array comprising force-sensing resistors (FSRs) co-located with a PicoPress puck reference sensor. Initial validation under stepped bandage pressures (10–60 mmHg) yielded linear agreement between the calibrated outer FSR and the puck reference ($R^2 = 0.999$), confirming reliable pressure quantification. The platform generates controlled, repeatable boundary conditions to support finite element (FE) modelling of garment–tissue interactions.

Introduction

Compression garments are widely used across clinical (venous disease, lymphoedema management), sports recovery, and load-bearing/military contexts [1,2]. Despite their prevalence, characterizing the spatially varying, time-dependent pressure field they impose on the underlying limb remains challenging. Standard fabric characterization relies on uniaxial or biaxial strip tests, which capture constitutive material behaviour but lack anatomical realism [3]. Cylindrical phantom approaches offer circumferential loading yet are constrained to fixed diameters and limited surface compliance variation. Ad-hoc rigs frequently suffer from inconsistent sensor seating, poor repeatability, and limited integration of multi-modal measurement. Critically, none of these approaches readily provides the boundary conditions needed to drive predictive FE simulations of internal tissue and vascular response.

This work addresses that gap by presenting the design, build, and initial validation of a modular compression test rig that is adjustable in anthropometry, compatible with standard pressure sensing and Digital Image Correlation (DIC), and capable of generating repeatable, quantitative pressure maps to inform computational models.

Platform Design

The rig was designed around five core requirements: (i) adjustable anthropometry covering XS–XL (nominal diameters 60–165 mm) via quick-change interlocking rings; (ii) continuous circumferential loading with lengthwise segmentation to emulate calf, knee, and thigh zones; (iii) a sensorised surface compatible with puck sensors (PicoPress/Kikuhime) and optionally DIC-friendly outer skins; (iv) modular silicone liners/sleeves attached magnetically for rapid swap, with variable thickness and compliance to bracket realistic muscle and adipose tissue conditions; and (v) a standardized seating and rest protocol with repeatable landmarking along the limb length.

The structural core consists of a rigid central skeleton with swappable diameter modules and fine adjustment via interlocking pads (Fig. 1). Silicone sleeves are profiled to maintain a near-circular outer interface under wrap tension, ensuring stable garment fit across sizes. Force-sensing resistors (FSR; 10 mm diameter, 0.3 mm thickness, accuracy ±5% at 50% full-scale) are positioned on the outer skin surface and at the inner (bone-surface) interface to quantify both the applied skin-level pressure and the pressure transfer through the silicone analogue. Modular actuator mounts support quasi-static seating and dynamic (cyclic/step) loading trials.

Validation Protocol

Initial validation was conducted using a compression bandage wrapped over one limb section fitted with a silicone sleeve. A PicoPress puck sensor (reference) and a co-located outer FSR were positioned at the same axial level; an internal FSR was mounted directly beneath at the same location. Pressure was applied in stepped increments of 10 mmHg from 10 to 60 mmHg, with each level held for approximately 10 s and the sensor zeroed between steps. A minimum of three replicates were collected per step to assess re-don and measurement repeatability. Ambient temperature was recorded throughout. FSR analogue-to-digital converter (ADC) outputs were converted to mmHg via a calibration curve, and outer vs. puck and internal vs. puck transfer functions were derived by linear regression.

Results and Discussion

The outer FSR demonstrated linear, high-fidelity agreement with the PicoPress reference across the full 10–60 mmHg range (fit: $F_{o}^{uteR} = 1.403 \times P^{Ico} + 0.067$; $R^2 = 0.9986$, RMSE = 0.90 g), confirming that the outer sensor array is trustworthy after calibration. The internal FSR similarly tracked external pressure closely but exhibited a small negative offset (fit: $F^{Int} = 1.429 \times P^{Ico} - 3.333$; $R^2 = 0.9978$, RMSE = 1.15 g), consistent with partial load redistribution through the silicone liner as expected from its mechanical compliance.

These results confirm that (i) the rig and sensors behave linearly and predictably within the clinically relevant pressure range, (ii) FSR counts can be reliably converted to mmHg via a single-pass calibration, and (iii) a characterized internal–external transfer function can be applied to infer sub-surface pressure from skin-surface measurements. Preliminary trials with commercially available 15–40 mmHg medical compression garments revealed heterogeneous circumferential pressure profiles, with measured values ranging between 12–32 mmHg depending on limb size and garment architecture, consistent with prior reports of spatially non-uniform loading [4,5].

Remaining characterization work includes: quantifying re-don repeatability across replicate sets; assessing FSR drift and hysteresis over sustained loading; mapping how the internal–external transfer function varies with silicone thickness and garment fabric architecture; and extending validation to DIC-based surface kinematic tracking under dynamic compression cycles. Calibrated pressure maps from the rig are being used to parameterize FE simulations (FEBio/ANSYS) of limb–tissue–garment interactions, including poroelastic tissue deformation and vessel compression scenarios.

Conclusion

A modular, anthropometry-aware compression test rig has been designed, built, and initially validated against a reference puck sensor. High-fidelity linear agreement ($R^2 > 0.997$) between calibrated FSR arrays and a PicoPress reference confirms the platform's suitability for repeatable, quantitative pressure characterization across clinically relevant ranges. By combining whole-limb circumferential pressure mapping, variable-compliance silicone tissue analogues, and multi-modal sensing (FSR + DIC), the platform provides the controlled boundary conditions needed to drive and validate FE predictions of internal tissue and vascular response. The system supports garment design verification, quality assurance, and input to evolving pressure–dosage standards for both medical and load-bearing/military applications.

Acknowledgements

This work was funded by the UK Defence Science and Technology Laboratory (Dstl) through the Defence Materials Centre of Excellence (DMEx) programme. The authors thank Dr Dean Fletcher and the DMEx team for their continued support.

References

[1] S. Zampelis, L. Vrancken, H. Niskanen, P. Malmberg, L. Henriksson and M. Ryden: IEEE Access Vol. 10 (2022), p. 12245–12256.
[2] L. Ren, Q. Tang, J. Zhao and D. Li: Biomech. Model. Mechanobiol. Vol. 18 (2019), p. 85–97.
[3] M. R. MacIntyre, H. A. Shearman, P. R. Wilcox and J. P. Morrison: Text. Res. J. Vol. 89 (2019), p. 1234–1245.
[4] R. R. Tirlapur, T. L. Barrett and S. J. Elvin: Sports Med. Vol. 47 (2017), p. 203–216.
[5] A. J. Kruger, K. L. McLeod and N. A. Myburgh: Med. Eng. Phys. Vol. 43 (2017), p. 45–52.