Dhivya Sugumaran,[1] Samuel Wesley [2]
[1] Junior Faculty, School of Fashion Design, Footwear Design and Development Institute, Kancheepuram, 602117, India
[2] Department of Fashion Technology (Apparel production), National Institute of Fashion Technology, Chennai 600113, India

Customization of Brassiere Underwire Design: Leveraging 3D Printing for Enhanced Pressure Distribution

Individualna prilagoditev oblike oporne žice v nedrčku: uporaba 3-D tiska za izboljšano porazdelitev pritiska

Original scientific article/Izvirni znanstveni članek
Received/*Prispelo* 2–2025 • Accepted/*Sprejeto* 11–2025

Corresponding author/*Korespondenčna avtorica:*
Dhivya Sugumaran
E-mail: writetodhivi@gmail.com; dhivya@fddiindia.com
ORCID iD: 0000-0002-1585-6907

Abstract

Conventional brassiere underwires often cause discomfort due to localized pressure concentrations, leading to wearer discomfort and potential long-term health concerns. This study investigates the application of 3D printing technology for designing and fabricating customized brassiere underwires aimed at improving pressure distribution and structural comfort. A 3D body scan of the under-bust profile was utilized to develop a personalized underwire model, which was fabricated using fused deposition modelling (FDM) with acrylonitrile butadiene styrene (ABS) material. To evaluate performance, pressure exertion tests were conducted using force-sensitive sensors positioned at three anatomical points, Point A (base region), Point B (medial region, near the sternum) and Point C (lateral region, near the underarm), under both static and dynamic conditions. The 3D-printed underwire demonstrated significant reductions in localized pressure compared to the conventional stainless-steel underwire, achieving decreases of 36.36% at Point A, 38.10% at Point B and 35.00% at Point C under static conditions, and 24.00%, 21.74% and 22.22%, respectively, under dynamic conditions. Complementary finite element analysis (FEA) was performed to simulate structural deflection under breast loads ranging from 0.5 kg to 0.8 kg. The results indicated that the maximum deflection increased from 1.48 mm to 2.37 mm, while average deflection rose from 0.80 mm to 1.28 mm, demonstrating a linear elastic behaviour consistent with the mechanical properties of ABS (Young's modulus ≈ 2.0 GPa) compared to stainless steel (≈ 200 GPa). The deformation contour confirmed effective load distribution with minimal deflection in the constrained regions, validating structural stability. Overall, the findings establish that 3D-printed ABS underwires provide improved comfort, controlled flexibility and reliable mechanical performance, making them a viable alternative to traditional metallic underwires. This research highlights the potential of additive manufacturing in the intimate apparel industry, enabling mass customization, enhanced anatomical conformity and improved wearer satisfaction beyond conventional mass-produced designs.

Keywords: 3D printing, brassiere, underwire, comfort, pressure distribution, FEA

Izvleček

Konvencionalne oporne žice (opornice) v nedrčkih pogosto povzročajo nelagodje zaradi lokaliziranih koncentracij pritiska, kar vodi v nelagodje pri nošenju in morebitne dolgoročne zdravstvene težave uporabnice. Ta raziskava se osredinja na uporabo tehnologije 3-D tiska za oblikovanje in izdelavo prilagojenih opornic za nedrčke, katerih namen je izboljšati porazdelitev pritiska in strukturno udobje. Na podlagi 3-D skeniranega profila podprsja je bil z uporabo modeliranja taljenega nanosa (FDM) z materialom akrilonitril butadien stiren (ABS) izdelan posamezni osebi prilagojen model opornice. Učinkovitost kosti je bila ocenjena iz rezultatov testiranja pritiska s pomočjo senzorjev za silo, nameščenih na treh anatomskih točkah: točki A (osnovno območje), točki B (medialno območje, blizu prsnice) in točki C (lateralno območje, blizu pazduhe), in sicer v statičnih in dinamičnih razmerah. 3-D natisnjena opornica je pokazala znatno zmanjšanje lokaliziranega pritiska v primerjavi s konvencionalno opornico iz nerjavnega jekla, in sicer zmanjšanje za 36,36 % v točki A, 38,10 % v točki B in 35,00 % v točki C v statičnih razmerah ter 24,00 %, 21,74 % oziroma 22,22 % v dinamičnih razmerah. Za simulacijo strukturnega odklona pri obremenitvah prsi od 0,5 kg do 0,8 kg je bila uporabljena metoda končnih elementov (MKE). Pokazalo se je, da se je največji odklon povečal z 1,48 mm na 2,37 mm, povprečni odklon pa z 0,80 mm na 1,28 mm, kar kaže na linearno elastično obnašanje, ki je skladno z mehanskimi lastnostmi ABS (Youngov modul ≈ 2,0 GPa) v primerjavi z nerjavnim jeklom (≈ 200 GPa). Kontura deformacij je potrdila učinkovito porazdelitev obremenitve z minimalnim odklonom v omejenih območjih, kar je potrdilo strukturno stabilnost. Splošna ugotovitev je, da 3-D tiskane opornice ABS zagotavljajo izboljšano udobje, nadzorovano upogibljivost in zanesljivo mehansko delovanje, kar pomeni, da so primerna zamenjava za tradicionalne kovinske opornice. Ta raziskava poudarja primernost aditivne izdelave v proizvodnji spodnjega perila, ki omogoča množično izdelavo po meri, izboljšano anatomsko skladnost in zadovoljstvo uporabnic, ki presega običajne konfekcijsko proizvedene modele.

Ključne besede: 3-D tiskanje, modrček z oporo, udobje, porazdelitev pritiska, metoda končnih elementov (MKE)

1 Introduction

The evolving lifestyle and diverse needs of modern women have profoundly influenced the design of clothing, particularly in the domain of lingerie. With the increasing physical and mental demands of daily life, comfort has become a fundamental requirement for maintaining productivity, well-being and confidence. Recognizing that each woman has unique body characteristics and personal preferences, lingerie designers and manufacturers are increasingly adopting personalization and customization as key strategies in garment development. Recent research demonstrates that the use of inverse design methods can successfully customize bra cups, thereby significantly improving fit and user satisfaction. This evolution emphasizes the necessity of integrating engineering principles into garment design to achieve optimal comfort, support and aesthetic appeal [1].

Anatomically, the female breast is a complex structure composed of mammary glands, adipose tissues, connective tissues and blood vessels, enclosed by a sensitive skin layer that contributes to femininity and physical appearance. Unlike other body parts, the breasts lack direct muscular and skeletal support and instead rely on Cooper's ligaments and superficial fascia for lift and positioning. These ligaments, however, are highly susceptible to mechanical stress during physical movement, which can lead to breast ptosis (sagging). Consequently, the design of brassieres that provide both comfort and adequate support has become increasingly important. Over the years, brassieres have evolved from simple functional garments into highly engineered support systems that integrate biomechanics, material science and ergonomic design. A well-fitted brassiere is crucial for minimizing breast discomfort, preventing musculoskeletal strain and enhancing posture [2].

Studies have shown that ill-fitting brassieres can cause shoulder pain, back pain and discomfort, particularly among women with larger bust sizes [3]. Among various bra types, underwire brassieres play a vital role in shaping and supporting the breasts. The underwire, typically a rigid U-shaped component made of metal or plastic, is sewn into a channel beneath the cups, providing lift and maintaining contour. To prevent the wire from piercing the fabric, both ends are covered with plastic tips or cushion caps [4]. Metallic materials, primarily steel and nickel-titanium alloys, dominate underwire production due to their superior rigidity and durability [5]. In contrast, plastic underwires, usually made from polypropylene or PVC, account for a small market share because of their lower stiffness and susceptibility to permanent deformation under load. However, ABS offers enhanced tensile strength, thermal resistance, and dimensional stability compared to other thermoplastics, making it a promising candidate for underwire applications requiring structural performance.

Research has confirmed that underwired brassieres effectively reduce vertical breast displacement and improve breast positioning, thereby enhancing support [6]. Continued advancements in underwire materials and geometry have also improved comfort by minimizing localized pressure points and improving ergonomic performance [7]. Nevertheless, many women report discomfort from underwires due to excessive stiffness and pressure concentration along the chest wall. Poorly fitted underwires can lead to skin irritation, inflammation and pressure-related pain [8]. Common design flaws include improper curvature and arc length, which may cause the wire to poke through the fabric or rub against the skin [9]. Prolonged pressure from underwires has been associated with mastitis and myalgia, although no scientific evidence supports a causal link to breast cancer [10]. Additional discomfort often arises from shoulder strap pressure, compounding wearer dissatisfaction [11].

In this context, 3D printing (additive manufacturing) presents a promising solution for creating personalized lingerie components. This technology enables the fabrication of complex three-dimensional objects layer by layer from digital models, facilitating precise customization and geometric flexibility. The fashion industry has increasingly adopted 3D printing for producing jewellery, footwear, accessories and garments [12–14]. Techniques such as FDM facilitate the production of textile-like structures suitable for wearable applications [15]. The integration of 3D printing in lingerie design enables the creation of customized underwires tailored to individual body contours, thereby improving fit, comfort and aesthetic harmony [16]. Prior studies using 3D scanning to capture breast root contours have demonstrated the potential for developing personalized underwires that enhance anatomical conformity and wearer comfort [17]. Moreover, several brands and researchers are advancing toward mass personalization in intimate apparel through 3D body scanning, parametric modelling and data-driven fitting algorithms [18].

The aim of this study was to design and fabricate a customized brassiere underwire using 3D printing technology to achieve enhanced pressure distribution and user comfort. A 3D body scanning technique was employed to obtain an accurate under-bust profile, which was then processed into a digital model for additive manufacturing. The resulting ABS underwire was experimentally tested to measure pressure exertion at critical points, while FEA was conducted to evaluate its structural response under different load conditions. Comparative assessments with conventional stainless-steel underwires were performed to examine comfort and structural integrity. The outcomes provide valuable insights into integrating digital design and additive manufacturing in lingerie development for improved comfort, performance and personalization.

2 Materials and methods

2.1 Acquisition of 3D body scan and underwire design

The design and evaluation of the customized 3D-printed underwire began with the acquisition of the under-bust profile using a high-precision 3D body scanning technique. A participant with a brassiere size of 38C was selected for this study to represent an average larger-cup size, which typically experiences higher pressure concentration under the bust. The scanning was performed using a Shining 3D EinScan Pro 2X Plus, a structured-light 3D scanner known for its high accuracy and ability to capture fine surface details. The scanner was operated in handheld rapid mode, facilitating complete acquisition of the under-bust curvature without causing any discomfort to the subject.

The captured three-dimensional point cloud data was processed using Geomagic Design X software to reconstruct the anatomical under-bust curve and remove scanning noise or misalignment. The processed geometry provided an accurate digital representation of the breast root contour, which served as the basis for customized underwire design. Using computer-aided design (CAD) tools, the underwire was modelled with optimized curvature and width ratios to achieve balanced support and minimal localized pressure. Several iterative CAD simulations were performed to refine the geometry, ensuring a comfortable anatomical fit and effective pressure dispersion.

The final design consisted of two main structural components: a cup portion and a flap portion. The cup portion, designed with a thickness of 1.5 mm and width of 2.5 cm, followed the natural curvature of the under-bust, tapering gradually toward the inner and outer breast regions. This design ensured a close fit along the chest wall while maintaining sufficient flexibility. The flap portion, measuring 4 mm in thickness and 7 mm in width, was connected to the lower edge of the cup. Its function was to distribute the applied load over a broader area, thereby reducing localized high-pressure points at the skin interface.

The completed 3D model was digitally aligned with the scanned under-bust surface to verify conformity and dimensional accuracy before proceeding to fabrication. The final assembly, illustrated in Figure 1, shows the precise fitting of the designed underwire onto the breast root curvature, confirming ergonomic and structural compatibility.

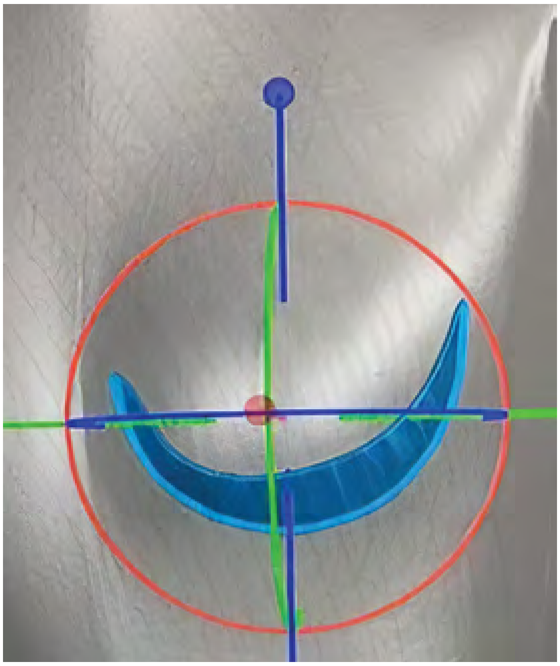

Figure 1: 3D model of underwire fitted along the breast root contour

2.2 3D Printing of underwire

The finalized 3D model of the customized underwire was fabricated using FDM, one of the most widely adopted additive manufacturing techniques for polymer-based components. This process was chosen for its cost-effectiveness, geometric versatility and ability to produce lightweight yet durable parts suitable for wearable applications. The printing was carried out using an Ultimaker S5 3D printer, which offers a high level of dimensional accuracy and surface quality appropriate for fine, curved geometries such as underwire structures.

ABS filament was selected as the printing material due to its superior mechanical properties, including high tensile strength, toughness and thermal stability. These characteristics make ABS ideal for producing components that require flexibility under cyclic loading without permanent deformation. The filament diameter used was 1.75 mm, while the printer's nozzle diameter was set to 0.4 mm. To achieve optimal strength and surface smoothness, the printing parameters were standardized as follows: printing temperature of 240°C, bed temperature of 100°C, printing speed of 50 mm/s and layer height of 0.1 mm. The infill density was maintained at 100% (solid) to ensure maximum structural integrity and consistent load-bearing performance.

The underwire was printed in a horizontal orientation to enhance dimensional stability and reduce internal stress accumulation during cooling. After printing, the component was allowed to cool gradually on the print bed to prevent warping or delamination. Post-processing involved support structure removal and light surface finishing using fine-grit sandpaper to achieve a smooth and skin-safe surface texture.

Figure 2. 3D printed underwire component

The printed underwire was subsequently evaluated for dimensional accuracy using digital callipers and was compared to the CAD model to confirm tolerance levels within ±0.2 mm. As illustrated in Figure 2, the 3D-printed underwire demonstrated high structural fidelity to the digital design. The fabricated underwire was then integrated into a specially prepared brassiere casing for experimental evaluation, as shown in Figure 3.

Figure 3: Attachment of 3D printed underwire in a casing with the cup

2.3 Pressure exertion test

Bra comfort is fundamentally influenced by the distribution of pressure exerted during wear, which can be assessed using direct or indirect evaluation methods [19]. Studies have shown that integrating cushioning elements between the bra strap and the body significantly enhances pressure distribution and overall comfort [20]. To evaluate the pressure exerted by the underwire on breast tissue, a pressure exertion test was conducted using force-sensitive resistor (FSR) sensors.

In this study, pressure mapping was performed following a customized test protocol designed to capture the pressure exerted at key anatomical regions beneath the breast. Based on ergonomic relevance and previous research [21], three critical sensor locations Point A (base region), Point B (medial region, near the sternum) and Point C (lateral region, near the underarm) were selected to measure both vertical and lateral support responses. These sensor locations were identified as areas prone to concentrated pressure during wear [22].

FSR sensors were affixed to the inner surface of the brassiere, directly below the underwire, ensuring precise alignment with the designated anatomical points. Each participant wore both types of brassieres: one fitted with a 3D-printed ABS underwire and another with a conventional stainless-steel underwire. The tests were conducted under controlled laboratory conditions to ensure consistency in posture, fit and motion. Pressure readings were collected under two states: static (stationary posture) and dynamic, which simulated natural body movements such as arm lifting, torso twisting and short walking cycles.

The sensors were calibrated prior to testing to ensure high measurement accuracy and repeatability. Pressure values were continuously recorded and expressed in N/cm², computed from the measured force and sensor's active area. The data collected from Points A, B and C provided a comprehensive representation of pressure distribution under both static and dynamic conditions, enabling a direct comparison between the two underwire types.

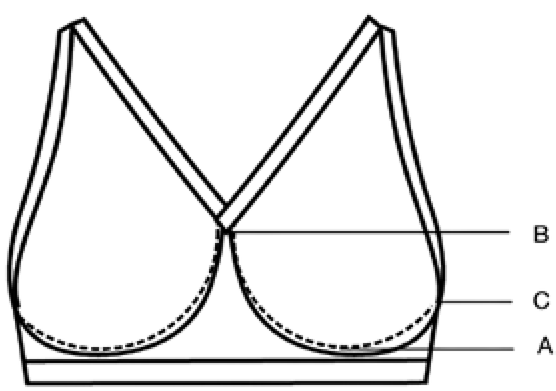

Figure 4: Sensor points A, B and C on the breasts

The spatial locations of the sensors and their corresponding measurement points are illustrated in Figure 4, which provides a schematic representation of the under-bust region showing the placement of Points A, B and C. This configuration ensured consistent data acquisition from regions most relevant to underwire-induced pressure during wear.

2.4 Finite element analysis (FEA)

Finite element analysis (FEA) was conducted using the ANSYS static structural module to evaluate the deflection behaviour of the 3D-printed underwire under varying loading conditions. A fine mesh was generated using tetrahedral solid elements to ensure high accuracy in predicting stress and deformation. The underwire model was constrained at both ends to replicate its fixed attachment points within the brassiere frame.

A pressure boundary condition was applied along the curved surface of the underwire, corresponding to estimated breast loads in the range of 0.5–0.8 kg. This load interval represents the average breast weight for women with larger cup sizes, typically varying from approximately 500 grams to over 1 kilogram, and includes the expected range for a 38C cup size, as reported in previous anatomical studies [22]. The simulation was performed under static loading conditions using the standard ANSYS solver to ensure stable and realistic results.

Material properties corresponding to ABS were assigned based on standard reference values, including its Young's modulus and Poisson's ratio, to accurately model the material's mechanical behaviour. The deflection of the underwire was then computed under the distributed load to quantify deformation characteristics representative of real-world wearing conditions.

3 Results and discussion

3.1 Pressure exertion test

A pressure exertion test was conducted to assess the distribution of pressure applied by the underwires on the wearer's body, as this parameter directly influences comfort and ergonomic performance. Excessive localized pressure can lead to discomfort, irritation and long-term skin issues, making it essential to evaluate how different materials and structural modifications affect pressure distribution. The results of the pressure exertion test, summarized in Table 1, demonstrate that the 3D-printed underwire consistently exhibited lower pressure values under both static and dynamic conditions across all measurement points A (base region), B (medial region) and C (lateral region) compared to the conventional stainless-steel underwire, as depicted in Figure 5. Pressure values increased slightly during dynamic motion due to natural variations in force distribution. However, the 3D-printed underwire demonstrated superior adaptability and stability compared to the rigid stainless-steel design.

Table 1: Pressure testing results

Point	Pressure (N/cm²)			
	Static test		Dynamic test	
	3D-printed underwire	Stainless steel underwire	3D-printed underwire	Stainless steel underwire
A	0.28	0.44	0.38	0.50
B	0.26	0.42	0.36	0.46
C	0.26	0.40	0.35	0.45

Figure 5: Stainless steel underwire

The most significant reduction in pressure was observed at Point B (medial region), indicating improved comfort and better load redistribution in this area. This supports the effectiveness of the customized 3D-printed design in distributing force more evenly across the under-bust region. These findings are in line with prior studies emphasizing that softer and geometrically adaptive components can enhance wear comfort by minimizing high-pressure zones beneath the bust [19, 20].

A comparative analysis further revealed that the 3D-printed underwire achieved substantial pressure reductions relative to the conventional model. Under static conditions, the reductions were 36.36% at Point A, 38.10% at Point B and 35.00% at Point C. Under dynamic conditions, pressure reductions were 24.00% at Point A, 21.74% at Point B and 22.22% at Point C. These improvements are attributed to the enhanced flexibility and form-fitting nature of the ABS underwire, which allows it to conform more effectively to the natural body contours compared to its rigid stainless-steel counterpart.

No abrupt pressure spikes were detected in the 3D-printed underwire, indicating smoother and more uniform pressure transitions. A minor increase observed at Point B during dynamic movement suggests that localized geometric optimization in future design iterations could further improve comfort. Overall, the lower pressure values recorded for the 3D-printed underwire confirm its potential to reduce discomfort and irritation, particularly during prolonged wear. Furthermore, the dynamic test results validate its superior performance during motion, reducing transient pressure peaks and enhancing overall comfort. These outcomes demonstrate the feasibility of utilizing 3D printing to develop ergonomically optimized underwire designs that achieve improved pressure distribution and wearer satisfaction.

3.2 Finite element analysis (FEA)

FEA was conducted to examine the deformation characteristics of the 3D-printed ABS underwire under varying breast loads and to compare its performance with a conventional stainless-steel underwire of identical geometry. The results are presented in Table 2, which presents the maximum deflection values obtained for each load condition.

Table 2: Comparative FEA deflection results

Load (kg)	Maximum deflection (mm)	
	ABS underwire	Stainless steel underwire
0.5	1.48	0.015
0.6	1.78	0.018
0.7	2.08	0.021
0.8	2.38	0.024

A clear contrast was observed between the deformation behaviours of the two materials. The stainless-steel underwire, owing to its high stiffness (Young's modulus ≈ 200 GPa), exhibited minimal deflection across all load cases, with a maximum of 0.024 mm at 0.8 kg. Conversely, the ABS underwire, with a significantly lower Young's modulus of approximately 2.0 GPa, demonstrated greater but controlled flexibility, with deflections increasing from 1.48 mm at 0.5 kg to 2.38 mm at 0.8 kg. This gradual rise in deformation with increasing load indicates a linear elastic response, consistent with the mechanical properties of both materials.

The controlled deflection of the ABS underwire plays a key role in enhancing comfort by facilitating slight structural adaptability under load. Unlike the rigid stainless-steel wire, which confines the breast in a fixed position, the ABS underwire behaves as a compliant spring, absorbing and redistributing the applied load through elastic deformation. This flexibility helps minimize localized stress concentrations, particularly at the medial and lateral regions identified during the pressure exertion tests, thereby reducing wearer discomfort.

The deflection results of the ABS underwire obtained from the finite element analysis (FEA) are illustrated in Figure 6, which presents a line chart showing the deflection variation along the underwire's bottom edge curve for breast weights ranging from 0.5 kg to 0.8 kg. The deflection values were analysed in terms of minimum, maximum and average magnitudes for each load case. At a 0.5 kg load, the minimum deflection recorded was 2.53×10^{-17} mm, the maximum value was 1.4848 mm and the average value was 0.8031 mm. For 0.6 kg, these values increased to 3.04×10^{-17} mm, 1.7818 mm and 0.9637 mm, respectively. Similarly, at 0.7 kg, the minimum deflection reached 3.54×10^{-17} mm, the maximum was 2.0788 mm and the average was 1.1243 mm. Under the highest tested load of 0.8 kg, the minimum, maximum and average deflections were 4.05×10^{-17} mm, 2.3758 mm, and 1.2850 mm, respectively.

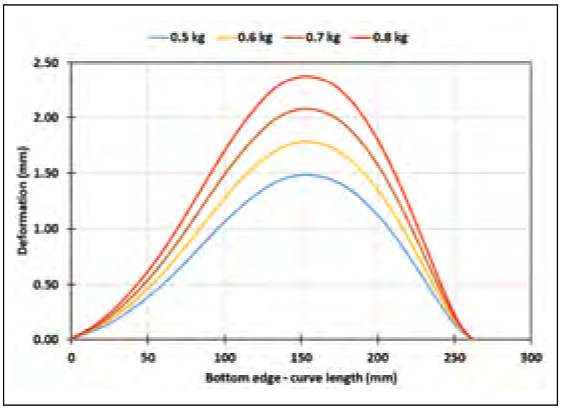

Figure 6: Finite element analysis line chart showing deflection of the ABS underwire for breast weights ranging from 0.5 kg to 0.8 kg

A comparison across the four load cases shows a nearly linear increase in deflection with increasing load. The maximum deflection rose by approximately 23.2% between 0.5 kg and 0.6 kg, by 16.7% between 0.6 kg and 0.7 kg, and by 14.3% between 0.7 kg and 0.8 kg, reflecting a gradually decreasing rate of increase. The consistent proportionality between load and deflection demonstrates that the ABS underwire behaves elastically within the tested range and maintains structural integrity under incremental loading conditions.

The FEA deflection contour of the ABS underwire, illustrated in Figure 7, shows that the maximum deformation occurred near the central region of the underwire where the downward breast load is concentrated while the end regions, constrained within the brassiere frame, exhibited minimal deflection. This deformation pattern indicates that the underwire effectively distributes the applied load along its curvature, minimizing local stress concentrations and preventing structural instability.

Overall, the analysis confirms that the 3D-printed ABS underwire exhibits controlled deflection behaviour under loads ranging from 0.5 kg to 0.8 kg, maintaining sufficient stiffness to support the breast while providing the flexibility needed to enhance comfort. The relatively low maximum deflection values demonstrate that the structure can withstand typical breast weights without excessive bending, while the distributed deformation pattern ensures uniform support. These findings validate the mechanical feasibility of 3D-printed ABS underwires as a comfortable, adaptive and structurally reliable alternative to traditional metallic underwires in brassiere design.

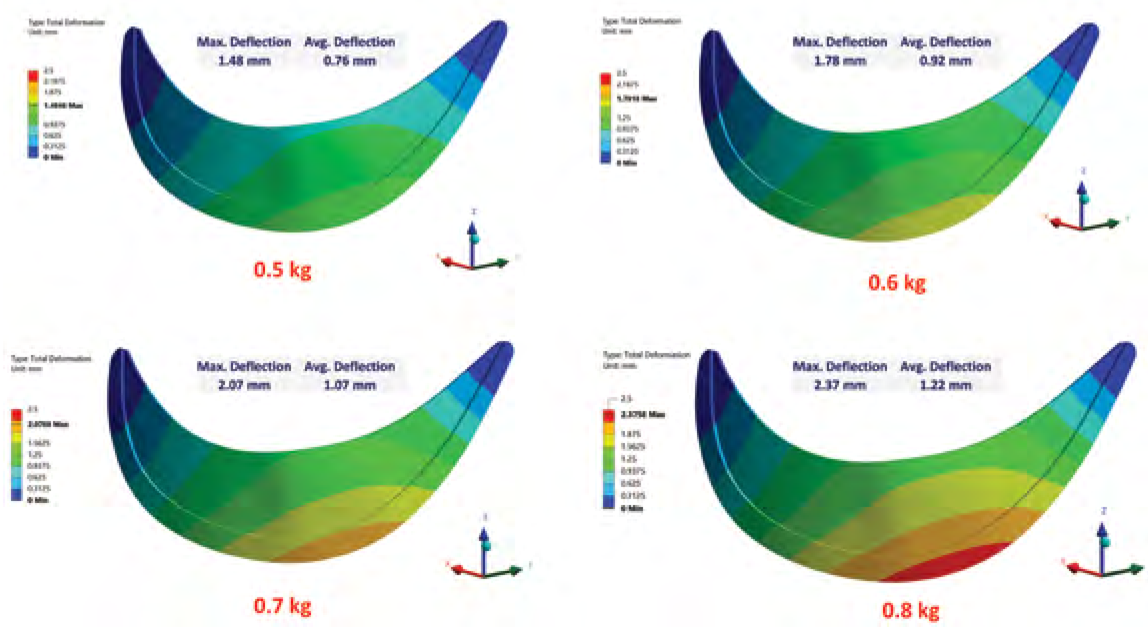

Figure 7: ABS underwire deflection distribution contour visualization for breasts weights of 0.5 kg to 0.8 kg

4 Conclusion

This study successfully demonstrated the potential of 3D printing technology in the customization of brassiere underwires to enhance wearer comfort and optimize pressure distribution. The primary objective to design a personalized underwire tailored to an individual's under-bust profile was achieved through 3D body scanning and digital modelling techniques. The fabricated underwire, produced using FDM with ABS material, offered a structurally stable and ergonomically comfortable alternative to conventional stainless-steel underwires.

The pressure exertion test results confirmed that the 3D-printed underwire effectively reduced localized pressure at critical contact points under both static and dynamic conditions. Compared to traditional stainless-steel underwires, the 3D-printed design achieved substantial reductions in localized pressure at all three measured points, resulting in a more uniform force distribution. This improvement directly translated to enhanced wearer comfort and mitigated discomfort commonly associated with rigid metallic underwires.

The FEA results further validated the mechanical reliability of the 3D-printed underwire under varying breast load conditions. The deformation contour indicated that the highest deflection occurred at the central region, where breast load concentration is greatest, while maintaining structural stability across the overall geometry. This pattern confirmed the ability of the customized design to distribute applied loads efficiently without excessive deformation, aligning with the pressure test findings.

Overall, this research highlights the feasibility and effectiveness of 3D-printed underwires as a viable alternative to conventional metallic designs. The ability to customize underwires based on individual anatomical profiles introduces a personalized approach to lingerie design, improving both comfort and functional support. Future studies may further refine this concept by exploring alternative materials, composite filament blends and optimized structural geometries to enhance flexibility and long-term durability.

Additionally, future studies should include comparative assessments between 3D-printed ABS underwires and conventional moulded plastic underwires, thereby establishing a broader understanding of the advantages and trade-offs associated with different fabrication techniques. Expanding the study to encompass multiple participants across a wider range of cup and band sizes will provide deeper insights into variations in fit, comfort and pressure distribution.

The findings from this research provide valuable guidance for lingerie designers and manufacturers, emphasizing the potential of digital design integration and additive manufacturing in intimate apparel development. The demonstrated approach facilitates mass customization, improved anatomical conformity and potentially more sustainable production models. Ultimately, the adoption of such advanced design methodologies could lead to underwires that are tailored to individual body scans, offering improved comfort, durability and fit across diverse body types, paving the way for a new generation of custom-fitted, high-comfort brassiere solutions.

Declaration of conflict of interest: The authors hereby declare that there are no potential conflicts of interest concerning the research, authorship and/or publication of this article.

Funding: The authors received no financial support for the research, authorship and/or publication of this article.

Data availability statement: Since 20 November 2025, the research dataset has been available at https://zenodo.org/records/17662950.

References

1. GUO, Z., ZHANG, Y., CHEN, J., LONG, Y., DU, L., ZOU, F. Study on realizing the personalized customization of bra cup by solving the inverse problem of bra cup design. *Textile Research Journal*, 2021, **91**(23–24), 2995–3011, doi: 10.1177/00405175211016560.
2. MCGHEE, D.E., STEELE, J.R., ZEALEY, W.J., TAKACS, G.J. Bra–breast forces generated in women with large breasts while standing and during treadmill running: Implications for sports bra design. *Applied Ergonomics*, 2013, **44**(1), 112–118, doi: 10.1016/j.apergo.2012.05.006.
3. WHITE, J., SCURR, J. Evaluation of professional bra fitting criteria for bra selection and fitting in the UK. *Ergonomics*, 2012, **55**(6), 704–711, doi: 10.1080/00140139.2011.647096.
4. SHIN, K., NG, S.P., LIANG, M. A geometrically based flattening method for three-dimensional to two-dimensional bra pattern conversion. *International Journal of Fashion Design, Technology and Education*, 2010, **3**(1), 3–14, doi: 10.1080/17543260903460200.
5. CHEN, C.M., LABAT, K., BYE, E. Physical characteristics related to bra fit. *Ergonomics*, 2010, **53**(4), 514–524, doi: 10.1080/00140130903490684.
6. GIBSON, T.M., BALENDRA, N., USTINOVA, K.I., LANGENDERFER, J. Reductions in kinematics from brassieres with varying breast

support. *International Journal of Exercise Science*, 2019, **12**(1), 402–411, doi: 10.70252/bfxi5607.
7. SHIN, K. Patternmaking for the underwired bra: new directions. *The Journal of The Textile Institute*, 2007, **98**(4), 301–318, doi: 10.1080/00405000701503006.
8. WANG, L.Z., CHEN, D., LIN, B. Analysis of pressure distribution of brassiere's under wires. *Journal of Fiber Bioengineering and Informatics*, 2009, **2**(1), 20–24, doi: 10.3993/jfbi06200903.
9. CHAN, C.Y.C., YU, W.W.M., NEWTON, E. Evaluation and analysis of bra design. *The Design Journal*, 2001, **4**(3), 33–40, doi: 10.2752/146069201789389601.
10. CHEN, L., MALONE, K.E., LI, C.I. Bra wearing not associated with breast cancer risk: a population-based case-control study. *Cancer Epidemiology, Biomarkers & Prevention*, 2014, **23**(10), 2181–2185, doi: 10.1158/1055-9965.epi-14-0414.
11. MCGHEE, D. E., STEELE, J. R. How do respiratory state and measurement method affect bra size calculations? *British Journal of Sports Medicine*, 2006, **40**(12), 970–974, doi: 10.1136/bjsm.2005.025171.
12. LIM, H.W., CASSIDY, T.D. 3D printing technology revolution in future sustainable fashion. In *Sustainability in Textiles and Fashion. International Textiles & Costume Culture Congress (ITCCC), 25-26 Oct 2014, Jeonju, South Korea*, 2014, 1–4.
13. ELMELEGY, N.A. 3D printing the future of innovative shapes and materials in women fashion design. *Eurasian Journal of Analytical Chemistry*, 2017, **13**(3), 151–173.
14. FANGLAN, Z., KAIFA, D. Innovative application of 3D printing technology in Fashion design. *Journal of Physics: Conference Series*, 2021, **1790**(1), 1–9, doi: 10.1088/1742-6596/1790/1/012030.
15. DIAK, V., DIAK, A. Features and limitations of Fused Deposition Modelling (FDM) in obtaining textile-like structures. *Tekstilec*, 2024, **67**(4), 397–411, doi: 10.14502/tekstilec.67.2024106.
16. *Innovation and technology of women's intimate apparel.* Edited by W. Yu, J. Fan, S.C. Halock and S.P. Ng. Cambridge : Woodhead Publishing, 2014.
17. WANG, Z., SUH, M. Bra underwire customization with 3-D printing. *Clothing and Textiles Research Journal*, 2019, **37**(4), 281–296, doi: 10.1177/0887302x19857474.
18. LIU, Y., ISTOOK, C.L., LIU, K., WANG, J. Innovative method for creating fitted brassiere wire prototype based on transformation matrix algorithm. *The Journal of The Textile Institute*, 2017, **109**(1), 73–78, doi: 10.1080/00405000.2017.1326366.
19. YICK, K.L., KEUNG, Y.C., YU, A., WONG, K.H., HUI, K.T., YIP, J. Sports bra pressure: effect on body skin temperature and wear comfort. *International Journal of Environmental Research and Public Health*, 2022, **19**(23), 1–16, doi: 10.3390/ijerph192315765.
20. LU, M., QIU, J., WANG, G., DAI, X. Mechanical analysis of breast–bra interaction for sports bra design. *Materials Today Communications*, 2016, **6**, 28–36. doi: 10.1016/j.mtcomm.2015.11.005.
21. BOWLES, K.A, STEELE, J.R. Effects of strap cushions and strap orientation on comfort and sports bra performance. *Medicine and Science in Sports and Exercise*, 2013, **45**(6), 1113–1119, doi: 10.1249/mss.0b013e3182808a21.
22. KATCH, V.L., CAMPAIGNE, B., FREEDSON, P., SADY, S., KATCH, F.I., BEHNKE, A.R. Contribution of breast volume and weight to body fat distribution in females. *American Journal of Physical Anthropology*, 1980, **53**(1), 93–100, doi: 10.1002/ajpa.1330530113.
23. SUGUMARAN, D., WESLEY, S. Dataset: 3D printed Underwire insert in Brassiere [Data set]. *Zenodo*, 2025, doi: 10.5281/zenodo.17662951.