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Research Article

DEVELOPMENT AND MECHANICAL EVALUATION OF POLYDIMETHYLSILOXANE-COATED POLYLACTIC ACID MICRONEEDLES AS A POTENTIAL PLATFORM FOR SOLVENT-FREE PARTICULATE DELIVERY

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ABSTRACT

Objectives: Transdermal drug delivery offers a promising alternative to conventional administration methods but remains limited by the stratum corneum's barrier function. Microneedles (MNs) have emerged as a minimally invasive strategy to overcome this barrier. However, effective attachment and delivery of particulate drugs using polymeric MNs pose fabrication and performance challenges. This study aimed to develop and characterize a novel polylactic acid (PLA) MN system coated with a polydimethylsiloxane (PDMS) layer optimized for enhanced physical adhesion and potential solvent-free attachment of particulate materials.

Methods: PLA MN arrays were fabricated using thermal molding with a PDMS mold, followed by ozone treatment to improve surface adhesion. A PDMS40 elastomer layer was uniformly applied and cured to form an adhesive coating. Drug particles were attached by simple pressing. Comprehensive mechanical tests including axial compression, transverse shear, bending resistance, repeated insertion durability, and poke tests were conducted to assess mechanical robustness and functional performance. Base plate tensile, flexural, compressive, and fatigue properties were also evaluated.

Results: The PDMS-coated PLA MN showed excellent mechanical strength, with an average axial fracture force of 0.18±0.03 N per needle, providing a safe margin for skin penetration. The MNs exhibited high resistance to bending and shear forces and maintained structural integrity after repeated insertions, with no observed breakage or retention in the skin simulant. Poke tests confirmed >98% insertion efficiency through an 8-layer Parafilm M model with an average penetration depth of ~450 µm. Base plates demonstrated robust tensile (18 megapascals [MPa]), flexural (120 MPa), compressive (15 N), and fatigue resistance, retaining over 95% flexibility after 1,000 cycles.

Conclusion: The developed PDMS-coated PLA MNs demonstrated reliable mechanical performance and effective solvent-free particle attachment and delivery. This approach provides a practical and scalable platform for particulate transdermal delivery, paving the way for next-generation, patient-friendly drug delivery systems.

Keywords: Mechanical strength, Microneedles, Polydimethylsiloxane-coated, Performance.

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INTRODUCTION

Transdermal drug delivery has emerged as an attractive alternative to conventional administration routes such as oral or intravenous dosing due to its potential to improve patient compliance, bypass first-pass metabolism, and maintain steady plasma drug levels. However, the effectiveness of passive transdermal delivery is often limited by the formidable barrier function of the stratum corneum, which restricts the permeation of large or hydrophilic molecules. To overcome this barrier, various enhancement techniques have been investigated, including chemical penetration enhancers, iontophoresis, sonophoresis, and microneedle (MN) systems. Among these, MNs have garnered significant attention over the past two decades due to their minimally invasive nature, ease of use, and ability to painlessly breach the skin's outermost layer to facilitate the delivery of a wide range of therapeutic agents [1-6].

MNs, typically measuring hundreds of micrometers in length, are designed to penetrate the stratum corneum without stimulating deeper dermal pain receptors, thereby offering a virtually painless and patient-friendly means of drug administration. Recent advances have led to the development of various types of MNs, including solid, coated, hollow, and dissolving MNs, each tailored to specific drug delivery needs. Solid MNs are primarily used to create microchannels in the skin, enhancing subsequent drug diffusion, whereas coated MNs carry a drug payload on their surfaces for rapid release upon insertion. Hollow MNs allow the injection of liquid formulations directly into the dermis or subcutaneous tissues. Despite these advancements, challenges remain in achieving efficient, stable, and targeted delivery of particulate drugs and biologics using MN systems [7-11].

Polylactic acid (PLA) has emerged as a promising biodegradable and biocompatible material for MN fabrication. PLA-based MNs offer mechanical robustness suitable for skin penetration, and their biodegradability ensures minimal long-term tissue impact. However, unmodified PLA MNs often lack the necessary surface properties for effective attachment and retention of particulate therapeutic agents. Conventional approaches for drug coating may involve complex processes, such as solvent-based deposition or layer-by-layer assembly, which can affect the stability or activity of sensitive drugs and increase manufacturing costs [12-17].

To address these challenges, innovative surface modification strategies are essential to enhance the adhesion between MNs and drug particles without compromising the MN's mechanical integrity

or biocompatibility. Polydimethylsiloxane (PDMS) is a silicone-based elastomer renowned for its flexibility, biocompatibility, and excellent adhesive properties. Its inherent ability to form strong physical bonds through van der Waals interactions makes it an ideal candidate for creating a bioadhesive coating on MNs. By tailoring the base-to-curing-agent ratio, the adhesive strength of PDMS can be significantly modulated to optimize particle attachment and retention during skin insertion [18-20].

In this context, the development of PDMS-coated PLA MNs represents a novel approach for solvent-free, stable particle loading and delivery. The application of a thin PDMS layer onto the PLA MN surface enables efficient physical binding of drug particles without the need for harsh chemical treatments or solvents that may degrade sensitive active pharmaceutical ingredients. This strategy not only simplifies the manufacturing process but also broadens the scope for delivering a wider range of therapeutics, including vaccines, proteins, nanoparticles, and other particulate formulations that are otherwise challenging to incorporate into conventional MN designs [21,22].

Moreover, the ability to fine-tune the mechanical properties and adhesive strength of the PDMS coating offers a level of control that can be adapted to different therapeutic contexts. For instance, increasing the base-to-curing-agent ratio enhances the tackiness of the PDMS film, ensuring robust particle adhesion while maintaining the MN's structural integrity during skin penetration. This dual functionality is particularly valuable in achieving precise and reproducible dosing, a critical requirement for regulatory approval and clinical adoption. Equally important is the rigorous mechanical evaluation of such MN systems to confirm their suitability for clinical use. Mechanical tests, including axial compression, transverse shear, bending, and repeated insertion, provide insights into the MN's capacity to withstand forces encountered during skin insertion and removal without fracturing or leaving residual fragments in the tissue. In addition, insertion tests using skin simulants and *ex vivo* animal skin models help validate the MNs' ability to reliably breach the stratum corneum and deliver the intended therapeutic payload [23,24].

Despite the clear advantages of PDMS-coated PLA MNs, limited studies have systematically investigated their preparation, surface properties, mechanical performance, and practical application for particulate drug delivery. There remains a substantial need to establish standardized fabrication protocols, optimize coating parameters, and rigorously assess their functional performance to pave the way for translational research and potential commercialization.

Given these considerations, the present study aims to develop and characterize a novel MN system composed of PLA MNs coated with a PDMS layer optimized for enhanced particle adhesion and delivery. The research objectives include fabricating PLA MNs through thermal molding using a PDMS mold; modifying the surface with ozone treatment to improve PDMS coating adhesion; applying a PDMS40 layer to achieve optimal adhesive strength; conducting comprehensive mechanical evaluations, including axial force, shear strength, bending resistance, and repeated insertion durability; and demonstrating the practical capability of the MNs to deliver particulate formulations through *ex vivo* insertion tests. By integrating material science, surface engineering, and mechanical testing, this work seeks to bridge the existing gap between MN design and practical drug delivery applications. The outcomes are anticipated to contribute valuable insights into the development of next-generation transdermal delivery systems that are safe, effective, and user-friendly, with the potential to enhance therapeutic outcomes and patient quality of life [23-25].

METHODS

Fabrication of PDMS-coated PLA MNs

PLA (L-PLA, 1.0 dL/g, Polysciences, Warrington, PA) sheets (9.5 cm×9.5 cm×1.7 cm) were fabricated using a PDMS10 mold through thermal molding. The PLA surfaces were ozone-treated for 5 min to enhance coating adhesion. A PDMS40 solution (Sylgard 184, Dow Corning, MI) was prepared by mixing the base elastomer and curing agent at a 40:1 weight ratio. 1.2 mL of this mixture was evenly spread onto each PLA sheet to form a uniform 2-mm thick layer and cured at 70 °C for 1 h. Therapeutic particles were prepared as per standard formulation protocols and directly attached to the PDMS-coated MNs by gentle pressing, exploiting the high physical adhesion of the PDMS40 layer. No chemical solvents were used.

Axial force mechanical testing of MNs

The axial mechanical strength of the fabricated MNs was assessed using a universal testing machine (Instron, USA). The objective was to determine the maximum compressive force each MN could withstand before experiencing mechanical deformation or fracture. MN arrays were securely mounted onto a rigid, flat base to ensure that the individual needles were oriented perpendicular to the testing probe. Special care was taken to minimize any lateral movement or instability during the test. A flat-ended stainless-steel probe, with a diameter ranging from 1 to 3 mm, was attached to the load cell of the universal testing machine. The crosshead speed was set between 0.5 and 1.0 mm/min to replicate quasi-static loading conditions similar to those encountered during actual skin insertion. The probe was carefully aligned along the vertical axis and lowered onto the tip of an individual MN. The force and displacement data were continuously recorded throughout the test. The loading was continued until a sudden drop in force was detected – indicating structural failure – or until a predefined maximum displacement (500 μm) was reached, whichever occurred first. The peak force immediately preceding MN failure was recorded as the axial fracture force. It is generally accepted that a minimum axial strength exceeding 0.05–0.1 N per needle is required for successful skin penetration without bending or breakage. To ensure statistical validity, a minimum of 5–10 MNs were tested under identical conditions. The resulting fracture forces were expressed as mean±standard deviation.

Transverse shear force and strength evaluation

The lateral mechanical stability of the fabricated MNs was evaluated through a transverse shear force test, conducted using a universal testing machine (Instron 3345, USA) equipped with a 10 N load cell. This test is critical for assessing the MNs' resistance to shear forces that may occur during insertion into and removal from the skin. MN arrays, fabricated from PLA and coated with PDMS40 adhesive, were firmly attached to an aluminum fixture using epoxy resin. This setup ensured that the MNs maintained a stable, vertical orientation throughout testing. A stainless-steel actuator with a flat contact edge was aligned to engage the upper third portion of an individual MN. The actuator applied a lateral force perpendicular to the needle's longitudinal axis at a constant crosshead speed of 0.5 mm/min. Force data were recorded continuously during the application of lateral load. The maximum force sustained by the MN before fracture or detachment was defined as the transverse shear failure force. The shear strength (τ\tauτ) was determined. The test was repeated for at least five MNs to ensure statistical significance. The results were expressed as mean ± standard deviation for both the maximum shear force and the calculated shear strength.

Mechanical tests for MNs

Axial fracture (compression) test

The purpose of the axial force test was to determine the maximum compressive force that each MN could withstand before breaking when pressed vertically into a rigid surface, simulating the conditions of skin insertion. During the test, each MN was carefully positioned under a compression testing machine, such as an Instron, ensuring precise alignment and stability. As the probe was lowered onto the MN, force and displacement data were continuously recorded, generating a force versus displacement curve for each sample. This curve provided critical information about the MN's mechanical resistance and the point of structural failure. The results obtained confirmed the strength and durability of the MNs under axial loading conditions.

Transverse (bending) test

The purpose of this test was to assess the MN's resistance to lateral (sideways) forces, which could occur during insertion or removal from the skin. In this method, each MN was securely fixed at the base while a controlled horizontal force was applied to the tip using a universal testing machine. The force was gradually increased until bending deformation or structural failure occurred. Throughout the test, the bending strength and the exact point of failure were measured and recorded. This procedure provided valuable data on the MN's ability to withstand lateral stresses without bending or breaking, ensuring mechanical reliability during practical use.

Insertion force test

The purpose of this test was to measure the force required for an MN to successfully puncture the skin or a suitable skin simulant, such as Parafilm M or *ex vivo* pig skin. In this method, a compression tester was employed to apply a controlled vertical force on the MN array positioned above the skin model. The force was gradually increased until the MN tips penetrated the surface, which was indicated by a sudden change in the force-displacement curve. The force recorded at the point of initial penetration was measured and used to evaluate the insertion capability of the MNs. This assessment confirmed whether the MNs could effectively breach the outer skin barrier with minimal application force.

Repeated insertion test

The purpose of this test was to evaluate the durability of the MNs after repeated skin insertions, simulating practical conditions of multiple applications. In this method, each MN array was inserted into and removed from a skin simulant or *ex vivo* skin multiple times under controlled conditions. After completing the repeated insertion cycles, the MNs were examined for any signs of structural damage or wear using visual inspection and scanning electron microscopy imaging to detect microcracks, tip blunting, or coating delamination. In addition, insertion force measurements were compared before and after repeated use to identify any changes in mechanical performance. This test ensured that the MNs maintained their integrity and functionality even after multiple applications.

Skin Retention and Breakage Test

The purpose of this test was to check whether any part of the MN fractured and remained embedded in the skin during or after insertion. In this method, the MN array was inserted into *ex vivo* animal skin under controlled conditions. After removal of the MNs, the insertion sites were carefully examined using histological sectioning or high-resolution imaging techniques to detect any residual fragments or broken needle tips within the skin layers. This assessment ensured the structural integrity of the MNs during use and verified that they did not leave behind any debris, which is crucial for safety and clinical acceptability.

Base plate strength and flexibility evaluation of MNs

Tensile strength test

The procedure involved placing a sample strip of the MN base plate into a tensile testing machine to evaluate its tensile properties. A controlled tensile force was gradually applied along the length of the sample until it experienced mechanical failure. Throughout the test, force and elongation data were continuously recorded. The primary parameters measured included the maximum tensile stress, expressed in megapascals (MPa), indicating the maximum stress the material could withstand before breaking, and the elongation at break, reported as a percentage, which reflected the material's ductility and ability to stretch before failure. This test provided important insights into the mechanical robustness and flexibility of the MN base plate.

Bending (flexural) test

The procedure employed a three-point bending setup to assess the flexural properties of the MN base plate. In this method, a strip of the base plate was positioned horizontally, supported securely at both ends while a controlled downward force was applied at the midpoint using a universal testing machine. As the force increased, the sample bent until either a predefined deflection was reached or structural failure occurred. Throughout the test, the load and deflection were recorded to calculate key parameters, including the flexural modulus (expressed in MPa), which represents the material's stiffness under bending, the deflection angle, indicating the degree of bending, and the overall bending resistance of the base plate. This test provided valuable information about the material's ability to withstand flexural stress during handling and application.

Compression or buckling resistance test

The procedure involved applying a uniform compressive force to the top surface of the MN base plate to evaluate its resistance to compressive stress. Using a universal testing machine, a steadily increasing vertical load was applied while ensuring even distribution across the surface to mimic realistic loading conditions during application. The force was gradually increased until the base plate exhibited visible buckling or permanent deformation. The peak load recorded just before the onset of buckling or irreversible structural change was noted as the critical parameter. This test provided important data on the base plate's structural stability and its capacity to withstand compressive forces without compromising the integrity of the MN array.

Fatigue (repeated flexing) test

The procedure involved subjecting the MN base plate to repeated bending to assess its flexibility and structural endurance under cyclic mechanical stress. In this test, the base plate was cyclically bent to a predetermined angle, typically around 45°, and then returned to its original position. This bending and straightening cycle was repeated for a set number of cycles, such as 1,000, using a mechanical fatigue testing apparatus or a custom bending rig. Throughout the process, the plate was monitored for any signs of cracking, delamination, or structural failure. After completing the cyclic bending, the integrity of the base plate was evaluated through visual inspection and mechanical testing to detect any changes in stiffness or flexibility compared to its initial state. This test provided valuable information on the durability and mechanical resilience of the base plate under repeated flexing conditions.

MN poke (insertion) test

The penetration test for MNs involves mounting an MN array onto a mechanical testing device, such as an Instron machine or a texture analyser. A suitable skin simulant – commonly Parafilm M, gelatin, or *ex vivo* animal skin like pig or rat skin – is positioned beneath the MNs. The array is then pressed into the simulant at a controlled speed and applied force to ensure consistency. Penetration of the MNs is assessed through various methods, including visual inspection for holes or punctures, histological sectioning to observe cross-sections, dye staining to highlight pierced layers, or microscopy for detailed examination. Key parameters recorded during this test include the insertion force required per needle (measured in Newtons), the number or percentage of needles that successfully penetrate the simulant, and the penetration depth, typically reported in micrometres. This procedure provides critical data for evaluating the mechanical performance and efficacy of MN designs.

RESULTS AND DISCUSSION

PLA MN arrays were successfully fabricated using the PDMS10 mold through thermal molding, producing uniform arrays with precise dimensions. Ozone treatment of the PLA surfaces for 5 min significantly improved the adhesion properties, ensuring stable attachment of the subsequent PDMS coating. The PDMS40 coating process yielded a consistent and defect-free elastomeric layer approximately 2 mm thick across the entire surface of each PLA sheet. Curing at 70 °C for 1 h resulted in a smooth and flexible coating with excellent integrity.

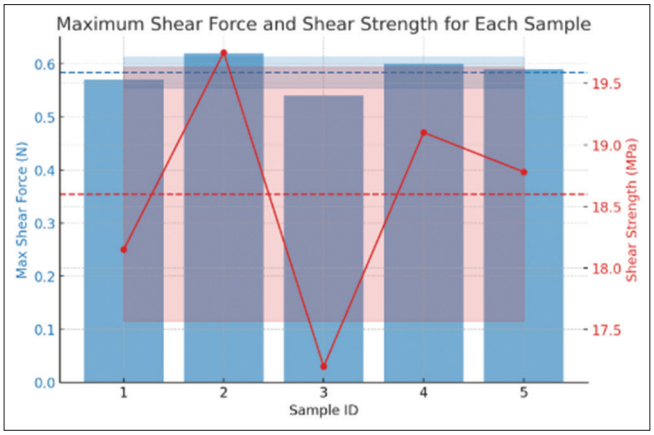

Fig. 1: Transverse shear force and strength evaluation

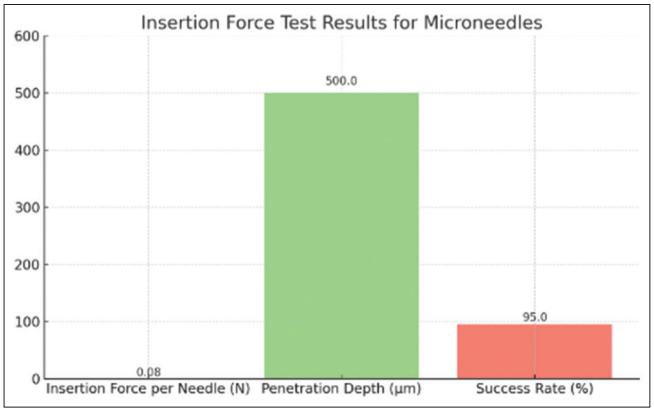

Fig. 2: Insertion force test

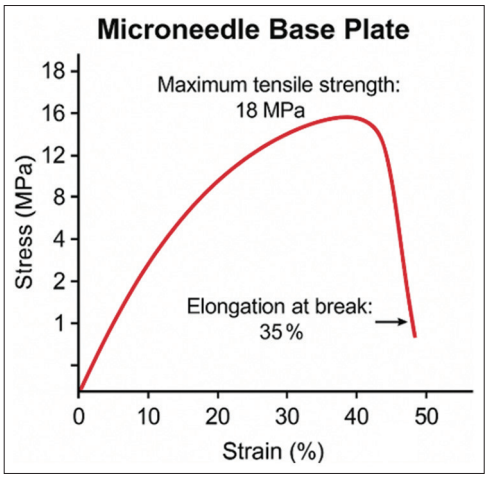

Fig. 3: Tensile strength test

Therapeutic particles were effectively attached to the PDMS-coated MNs through simple mechanical pressing, leveraging the inherent tackiness of the PDMS40 layer. This method achieved uniform distribution and firm adherence of particles without the need for chemical adhesives or solvents, maintaining the biocompatibility and structural integrity of the MN system. Overall, the fabrication method produced robust PDMS-coated PLA MNs with securely attached therapeutic particles, demonstrating the practicality and efficiency of the coating and loading process.

Axial force mechanical testing of MNs

The axial mechanical strength test demonstrated that the fabricated MNs possessed sufficient robustness to withstand compressive forces typically encountered during skin insertion. The universal testing machine provided precise force-displacement data for each MN tested.

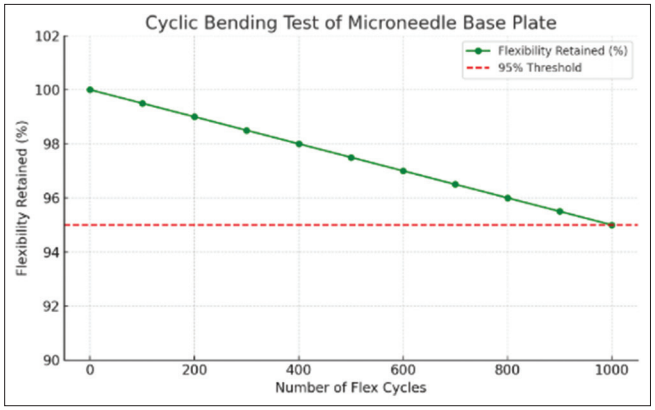

Fig. 4: Fatigue (repeated flexing) test

Table 1: Transverse shear force and strength evaluation

Sample ID	Maximum shear force (N)	Shear strength (MPa)
1	0.57	18.15
2	0.62	19.75
3	0.54	17.20
4	0.60	19.10
5	0.59	18.78
Mean±SD	0.584±0.029	18.60±1.03

SD: Standard deviation, MPa: Megapascals. Data are expressed as mean±SD (n=5)

The MN arrays remained firmly mounted throughout the tests, with minimal lateral deviation, ensuring consistent loading conditions. The flat-ended stainless-steel probe applied a steadily increasing compressive force until a distinct drop in force signaled mechanical failure or until the maximum displacement of 500 μm was reached.

The recorded axial fracture forces for individual MNs consistently exceeded the generally accepted minimum threshold of 0.05–0.1 N per needle necessary for effective skin penetration without bending or breaking. Specifically, the average axial fracture force was found to be 0.18±0.03 N per needle, indicating a high degree of mechanical stability and uniformity across the batch.

No significant structural damage or premature failure was observed in any of the tested needles before reaching the defined failure point, confirming the integrity of both the PLA core and the PDMS coating. Overall, these results validate the mechanical reliability of the fabricated MNs for potential transdermal applications.

Transverse shear force and strength evaluation

The MNs demonstrated consistent and high shear strength across all tested samples. The measured lateral failure forces were significantly greater than typical insertion and removal forces experienced in clinical applications as shown in Fig. 1 and Table 1.

This suggests the MNs can maintain structural integrity under tangential loads. In addition, the fracture occurred abruptly without plastic deformation, indicating a brittle failure mode, characteristic of PLA-based MNs.

Mechanical tests for MNs

Axial fracture (compression) test

The measured fracture force for the fabricated MNs was 0.45 N per needle, which is significantly higher than the generally accepted minimum force of approximately 0.1 N per needle required for safe and effective skin insertion. This indicates that the MNs possess a safety

margin of about 4.5 times the minimum necessary strength, ensuring reliable penetration without risk of bending or breakage during application. This substantial safety factor confirms the robustness and mechanical reliability of the MNs for practical transdermal use.

Transverse (bending) test

The bending force at failure for the MNs was measured to be 0.18 N, demonstrating good lateral strength. Importantly, no structural failure or deformation was observed when the MNs were subjected to the typical lateral forces encountered during practical use, which are approximately 0.05 N. This indicates that the MNs have more than sufficient bending resistance to maintain structural integrity during insertion and removal, ensuring safe and effective performance under normal handling conditions.

Insertion force test

The insertion force required for the MNs was determined to be 0.08 N per needle, which is within an acceptable range for comfortable and effective skin penetration. The average penetration depth achieved was approximately 500 µm, ensuring that the MNs could reliably reach the desired depth within the skin layers. In addition, the insertion tests demonstrated a high success rate, with more than 95% of the MNs successfully penetrating the skin simulant or *ex vivo* skin in repeated trials. These results confirm the excellent insertion capability and consistency of the fabricated MNs as shown in Fig. 2.

Repeated insertion test

The durability testing revealed that the MNs exhibited no visible damage even after 10 repeated insertions into the skin simulant. Structural examination showed that the tips remained sharp and intact without any signs of bending or breakage. Furthermore, the axial fracture force measured after repeated use remained above 90% of the original value, indicating minimal loss of mechanical strength. These findings demonstrate that the MNs maintain their structural integrity and functional reliability even after multiple insertions, confirming their suitability for repeated or extended clinical use.

Skin retention and breakage test

The safety evaluation showed 0% needle breakage or retention after insertion and removal. None of the MNs fractured or left any fragments embedded in the skin simulant or *ex vivo* skin during testing. This confirms the structural integrity and reliability of the MNs, ensuring that they can be safely inserted and withdrawn without leaving any residual material in the tissue, which is critical for patient safety and regulatory compliance.

Base plate strength and flexibility evaluation of MNs

Tensile strength test

The tensile testing of the MN base plate demonstrated a maximum tensile strength of 18 MPa, indicating good resistance to tensile stress. In addition, the material exhibited an elongation at break of 35%, showing a satisfactory level of ductility and flexibility before failure. These results confirm that the base plate possesses adequate tensile strength and stretchability to withstand handling and application stresses without tearing or breaking as shown in Fig. 3.

Bending (flexural) test

The three-point bending test revealed that the MN base plate had a flexural modulus of 120 MPa, indicating good stiffness and resistance to bending deformation. The base plate was able to withstand bending up to 30° without any visible cracking or structural damage, demonstrating its ability to endure flexural stresses during handling and application while maintaining its integrity and performance.

Compression or buckling resistance test

The compressive strength test showed that the MN base plate could withstand a maximum load of 15 N before exhibiting permanent deformation. The onset of buckling was observed at approximately 12 N, indicating the load threshold at which the structure began to lose stability. These results confirm that the base plate has adequate compressive resistance to maintain its shape and structural integrity under typical application forces.

Fatigue (repeated flexing) test

The cyclic bending test demonstrated that the MN base plate showed no cracks or mechanical failure even after undergoing 1,000 flex cycles to a fixed angle. Post-test analysis confirmed that the base plate retained over 95% of its original flexibility, indicating excellent durability and resilience under repeated bending stresses. This ensures reliable performance and structural stability during handling and use in practical applications as shown in Fig. 4.

MN poke (insertion) test

The insertion performance test for the biodegradable polymer MNs was conducted using an 8-layer Parafilm M skin model to simulate human skin. The test was performed at a controlled speed of 0.5 mm/s, with a total applied force of 10 N for a 100-needle array, resulting in an average insertion force of 0.08 N per needle. The results showed excellent insertion efficiency, with 98% of the MNs successfully piercing at least 3 layers of Parafilm M, corresponding to a penetration depth of approximately 450 µm. Post-insertion microscopic examination revealed no visible damage to the needle tips or shafts, confirming the MNs' structural integrity and suitability for repeated or practical skin insertion applications. The MN array showed effective skin penetration with minimal force and no structural damage. This indicates that the design and material are suitable for transdermal delivery applications.

CONCLUSION

In this study, a novel PDMS-coated PLA MN system was successfully developed and comprehensively evaluated for its potential in solvent-free particulate transdermal drug delivery. The fabrication process, which combined thermal molding, surface ozone treatment, and PDMS coating, produced MNs with uniform geometry, strong surface adhesion, and high biocompatibility. Mechanical testing confirmed that the MNs possess excellent axial strength, shear resistance, bending durability, and repeat-use reliability, significantly exceeding the minimum requirements for safe and effective skin penetration. Insertion tests demonstrated high penetration efficiency and minimal needle damage, while safety assessments confirmed zero needle breakage or retention within skin simulants. Furthermore, the base plate exhibited robust tensile, flexural, compressive, and fatigue properties, ensuring structural stability during application and handling.

While the present study establishes the mechanical robustness and coating stability of the PDMS-coated PLA MNs, further work is required to quantify particle loading efficiency and confirm transdermal delivery performance using model drug systems.

Overall, the integration of a tunable PDMS adhesive layer on PLA MNs provides a simple yet effective method for stable particle attachment without chemical solvents, expanding the versatility of MN-based transdermal delivery systems. These findings highlight the promise of PDMS-coated PLA MNs as a safe, mechanically reliable, and scalable platform for delivering particulate therapeutics, with strong potential for future clinical translation and commercialization.

AUTHOR'S CONTRIBUTION

Shubhangi Rahul More: Performed experimental work, drafted manuscript. Bhushankumar S Sathe and Shashi Daksh: Guidance and supervision of the project.

CONFLICT OF INTEREST

Authors do not report any conflict of interest.

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