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Bioinspired Microfabricated Adhesive for Atraumatic Tissue Manipulation in Minimally Invasive Surgery

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***Abstract*—Minimally invasive surgery (MIS) has transformed modern healthcare by reducing patient trauma and recovery time; however, safe manipulation of delicate, soft tissues remains a major challenge. Conventional graspers frequently apply excessive compressive forces, leading to iatrogenic injury and postoperative complications. To address this issue, we present a bioinspired microfabricated adhesive surface designed for atraumatic tissue handling in wet surgical environments. The proposed design draws inspiration from the hierarchical fibrillar architecture of gecko footpads and employs biocompatible polyimide micropillar arrays fabricated via photolithography and reactive ion etching. The adhesive performance was systematically evaluated on ex vivo porcine tissues, including liver, heart, kidney, and spleen, under simulated physiological conditions. The influence of micropillar geometry—specifically diameter, height, and density—on adhesion strength and tissue safety was quantitatively analyzed using a custom-built micro-force measurement platform. The optimized configuration achieved an adhesion force of up to 4.2 N on cardiac tissue in phosphate-buffered saline, primarily driven by van der Waals and capillary interactions. Histological analysis confirmed minimal tissue trauma, with average damage scores reduced by more than 40% compared with conventional surgical graspers. These results demonstrate that gecko-inspired microstructured adhesives can provide strong, reversible, and controllable wet adhesion with negligible tissue damage. This work establishes a promising foundation for the development of next-generation minimally invasive surgical instruments that combine mechanical reliability with intrinsic tissue safety.**

Keywords—Bioinspired Adhesion, Microfabrication, Tissue Manipulation, Minimally Invasive Surgery, Gecko-Inspired, Atraumatic Grasping

1. INTRODUCTION

Minimally invasive surgery (MIS) has revolutionized modern surgical practice by reducing patient trauma, shortening recovery time, and improving cosmetic outcomes [1]. The effectiveness of MIS largely depends on the surgeon's ability to manipulate and retract soft tissues through narrow access points. However, conventional grasping instruments, typically equipped with toothed or serrated jaws, can generate excessive local stress during tissue handling. This often leads to iatrogenic injury such as crushing, tearing, or perforation, which may subsequently result in inflammation, bleeding, and impaired healing [2,3]. Quantitative studies of tool–tissue interaction have shown that excessive grasping force is a preventable source of surgical complications [4].

To mitigate such issues, alternative grasping technologies have been investigated, including soft robotic and vacuum-based systems [5]. Although soft robotic grippers can reduce localized pressure and tissue trauma, they frequently lack the holding strength required for complex surgical maneuvers [6]. Vacuum-assisted devices provide stronger adhesion but can cause surface damage and are often cumbersome to integrate into standard laparoscopic workflows. Hence, there remains a critical need for a grasping mechanism that offers secure, controllable, and reversible adhesion to wet biological tissues without inducing trauma.

Biological systems provide valuable inspiration for achieving such functions. For example, certain species can adhere strongly yet reversibly to a variety of surfaces through specialized micro- and nano-structured interfaces [7]. These natural mechanisms demonstrate that adhesion can be achieved without chemical bonding or surface penetration, motivating the development of synthetic biomimetic adhesives. However, replicating such mechanisms in the fluid-rich, compliant environment of the human body remains a formidable challenge. The presence of aqueous films and soft, irregular tissue surfaces weakens dry adhesion mechanisms and introduces complex interfacial interactions that limit their applicability in surgical settings.

To address these challenges, this study proposes a bioinspired microstructured adhesive specifically designed for atraumatic tissue manipulation during MIS. We hypothesize that by optimizing the geometry and material properties of micropillar arrays, it is possible to achieve

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sufficient reversible adhesion under wet conditions while minimizing tissue injury. The adhesive performance is evaluated across multiple ex vivo tissue types under simulated physiological conditions and compared with that of conventional surgical graspers. This work aims to provide a foundation for the development of next-generation atraumatic surgical tools that bridge the gap between bioinspired materials science and clinical application.

2. Related Work

The advancement of atraumatic grasping tools has been driven by three major research domains: the limitations of conventional surgical graspers, the emergence of bioinspired adhesion systems, and the adaptation of these principles to wet and dynamic biomedical environments.

2.1. Limitations of Conventional Surgical Graspers

Traditional laparoscopic instruments rely on compressive clamping to secure tissues. Although effective for mechanical stability, this approach inherently induces trauma to delicate structures [8][9]. The degree of damage correlates strongly with the magnitude of the applied force and the geometry of the grasper jaws [10]. Various strategies, such as padded jaws and force-limiting mechanisms, have been proposed to reduce tissue injury; however, these modifications often compromise gripping reliability, leading to slippage and extended procedure times. The persistent trade-off between secure grasping and tissue preservation continues to motivate the search for non-compressive, adaptive adhesion mechanisms.

2.2. Bioinspired Adhesion: From Nature to Engineering

Natural organisms offer numerous examples of reversible adhesion that operate through structural and physical rather than chemical means. Hierarchical fibrillar structures observed in certain species enable strong, residue-free adhesion through van der Waals interactions, inspiring the design of synthetic polymer-based dry adhesives with tunable surface geometry and stiffness [11][12]. Further studies have expanded this concept by introducing hierarchical or hybrid architectures that enhance conformability and load distribution across irregular surfaces [13]. Other biological systems, such as aquatic species that utilize protein-based glues or suction-based attachment, have inspired the development of materials and structures capable of maintaining adhesion in fluidic environments [14]. These insights collectively demonstrate that controllable and reversible adhesion can be achieved through design of surface topology and material mechanics.

2.3. Medical Adhesives for Wet Environments

Translating bioinspired adhesion concepts into medical applications introduces additional challenges, particularly the requirement for effective adhesion under wet, dynamic, and biocompatible conditions. One line of research has focused on hydrogels that form robust, reversible bonds via physical entanglement or interfacial crosslinking [15]. Another approach uses microstructured or microneedle-like surfaces to achieve mechanical interlocking with soft tissues while minimizing penetration depth [16]. These technologies have shown promise in applications such as wound sealing and tissue repair, yet their capacity for rapid, reversible adhesion suitable for dynamic manipulation remains limited. Optimizing the balance between adhesion strength, reversibility, and biocompatibility continues to be a key research challenge.

2.4. Research Gap and Our Contribution

While significant advances have been made in the design of both dry and wet adhesive systems, most have been optimized for static adhesion rather than dynamic tissue handling required in minimally invasive surgery [17]. Surgical manipulation demands secure yet easily releasable adhesion to soft, fluid-covered surfaces without damaging tissue integrity. To address this gap, the present study revisits bioinspired microstructured adhesion with the goal of achieving reversible, non-penetrating attachment suitable for surgical environments. By tailoring the microstructure geometry and material properties for wet conditions, we aim to create a surface that enables secure tissue handling with minimal trauma, thus providing a potential pathway toward safer and more effective minimally invasive instruments.

3. Methodology and System Design

This section details the systematic approach employed to design, fabricate, and evaluate the bioinspired micro-adhesive surface for surgical applications. The methodology was designed to ensure the reproducibility of our findings and to allow for a quantitative comparison with conventional surgical instruments.

3.1. Data Collection and Sampling

The adhesive surfaces were designed based on the fundamental principles of gecko adhesion, adapted for a wet biological environment (Figure 1). The primary design variables included micropillar diameter (D), height (H), and center-to-center spacing (P).

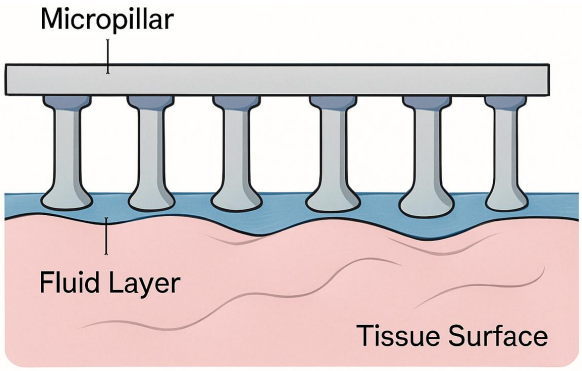

Figure 1. Schematic Illustration of the Bioinspired Adhesive Mechanism.

Cross-sectional view showing the micropillar array interacting with a soft tissue surface in the presence of a thin fluid layer (PBS). The compliant micropillars conform to the tissue micro-topography, maximizing contact area for van der Waals and capillary adhesion. A range of parameters was explored to investigate their influence on adhesion performance: diameters from 0.5 to 2.5 μm, heights from 0.5 to 2.0 μm, and spacings from 1 to 4 μm. This resulted in a library of 60 unique micropillar designs with varying aspect ratios (H/D) and densities (pillars/mm^2).

The micropillar arrays were fabricated from biocompatible polyimide (PI) using a top-down microfabrication process, as illustrated in the experimental workflow. The process is summarized as follows:

- Substrate Preparation: A 4-inch silicon wafer was used as the substrate. The wafer was cleaned using a standard piranha solution (H_2SO_4:H_2O_2 = 3:1) to remove organic residues.
- Photolithography: A negative photoresist (SU-8 2002, MicroChem) was spin-coated onto the silicon wafer to define the pillar locations. The pattern of circular dots was transferred to the photoresist using a UV mask aligner (MA6, SUSS MicroTec) or, for sub-micron features, an electron-beam lithography system (EBPG5200, Vistec).
- Master Mold Fabrication: The patterned photoresist served as a mask for a deep reactive ion etching (DRIE) process (AMS 200, Alcatel), which was used to etch the silicon wafer to the desired pillar height, creating a negative master mold.
- Polymer Casting: A liquid precursor of polyimide was poured over the silicon master mold. The sample was then cured in a nitrogen-purged oven at 350°C for 2 hours to form a solid PI film.
- Demolding: The cured polyimide film, now containing the micropillar arrays, was carefully peeled from the silicon master mold.
- Surface Characterization: The fabricated micropillar arrays were inspected using scanning electron microscopy (SEM) (Verios 460L, FEI) to verify the fidelity of the pillar geometry (diameter, height, and shape) and to check for defects.

3.2. Ex Vivo Tissue Preparation

To simulate the conditions of MIS, fresh porcine tissues were used for all adhesion experiments. Four different organ types were selected to represent a range of mechanical properties and surface characteristics encountered in abdominal and thoracic surgery: liver, heart, kidney, and spleen. All tissues were procured from a local abattoir and used within 4 hours of slaughter to ensure tissue viability. The tissues were cut into 3 cm × 3 cm samples, rinsed with phosphate-buffered saline (PBS, pH 7.4), and stored in PBS at 37°C until testing. During testing, the tissue surface was kept continuously moist with PBS to simulate the physiological environment.

3.3. Adhesion Force Measurement

A custom-built micro-force testing apparatus was constructed to measure adhesion forces. The system consisted of a high-precision 3-axis motorized stage (MTS50-Z8, Thorlabs), a sensitive load cell (GSO-10, Transducer Techniques, capacity 10g, resolution 0.1 mN), and a data acquisition system. The micropillar adhesive samples (5 mm × 5 mm) were mounted on the load cell.

The testing protocol for measuring normal (pull-off) adhesion force was as follows:

- The tissue sample was secured in a petri dish filled with PBS maintained at 37°C.
- The adhesive sample was lowered onto the tissue surface at a constant velocity of 100 μm/s.
- A preload force (0.1 N, 0.5 N, 1.0 N, or 2.0 N) was applied and held for a specified contact time (1, 5, 10, or 30 s) to ensure consistent contact.
- The adhesive sample was then retracted vertically at a constant velocity of 10 μm/s until complete detachment.
- The maximum negative force recorded during retraction was defined as the adhesion force (pull-off force).

Each measurement was repeated 10 times for each combination of design, tissue type, and environmental condition.

3.4. Tissue Damage Assessment

Tissue damage was evaluated using both macroscopic and microscopic methods immediately after the adhesion tests.

Macroscopic Assessment: Tissue samples were visually inspected by two independent observers who were blinded to the experimental conditions. Damage was graded using a 5-point scoring system adapted from previous studies [2, 8]:

- Score 0: No visible damage or indentation.
- Score 1: Minor surface indentation, fully recovers after 1 minute.
- Score 2: Visible indentation remains, minor surface abrasion, no bleeding.
- Score 3: Obvious tissue compression, surface tearing, or localized petechial hemorrhage.
- Score 4: Severe tissue damage, including deep tears, active bleeding, or perforation.

Microscopic Assessment: For a subset of samples, tissue was fixed in 10% neutral buffered formalin, embedded in paraffin, sectioned, and stained with Hematoxylin and Eosin (H&E). The stained sections were examined under a light microscope to assess cellular architecture, inflammation, and other signs of micro-trauma.

3.5. Comparative Study

To benchmark the performance of the bioinspired adhesive, a comparative study was conducted against a standard 5 mm laparoscopic grasper (Endo Grasp™, Medtronic). The grasper was used to grip the tissue samples with forces comparable to those used in clinical practice (1-5 N), as measured by the load cell. The resulting tissue damage was assessed using the same scoring system described above. The success rate of manipulation (defined as the ability to lift and hold the tissue for 30 seconds without slippage) was also recorded for both the adhesive and the traditional grasper.

3.6. Statistical Analysis

All quantitative data are presented as mean ± standard deviation. Statistical analysis was performed using Python with the SciPy and statsmodels libraries. A multi-factor Analysis of Variance (ANOVA) was used to determine the statistical significance of the effects of micropillar parameters, tissue type, and environmental conditions on adhesion force and tissue damage. Post-hoc comparisons were made using Tukey's Honestly Significant Difference (HSD) test. Linear regression analysis was used to model the

relationship between adhesion force and contact area. A Pearson correlation coefficient was calculated to assess the relationship between adhesion force and tissue damage. A p-value of less than 0.05 was considered statistically significant.

4. RESULTS

This section presents the experimental results, starting with the characterization of the fabricated micropillar arrays, followed by a systematic analysis of their adhesive performance on biological tissues, an evaluation of the associated tissue damage, and a direct comparison with conventional surgical instruments.

4.1. Fabrication and Characterization of Micropillar Arrays

We successfully fabricated 60 unique designs of polyimide micropillar arrays with varying diameters, heights, and spacings. SEM imaging confirmed the high fidelity and uniformity of the fabrication process. A representative SEM image shows the highly uniform cylindrical micropillars with smooth sidewalls and flat top surfaces, demonstrating the precision of our microfabrication technique. The micropillar geometries closely matched the design specifications. Figure 2 illustrates the distribution of the key design parameters across our library of fabricated adhesives. The diameters ranged from 0.5 to 2.5 μm, and the aspect ratios (H/D) were primarily concentrated between 0.4 and 2.0 (Figure 2A, 2B). The pillar density, a critical factor for adhesion, varied logarithmically with the inter-pillar spacing, covering a wide range from approximately 6 × 10^4 to 1 × 10^6 pillars/mm² (Figure 2C). The parameter space of diameter versus height shows the broad coverage of our experimental designs (Figure 2D).

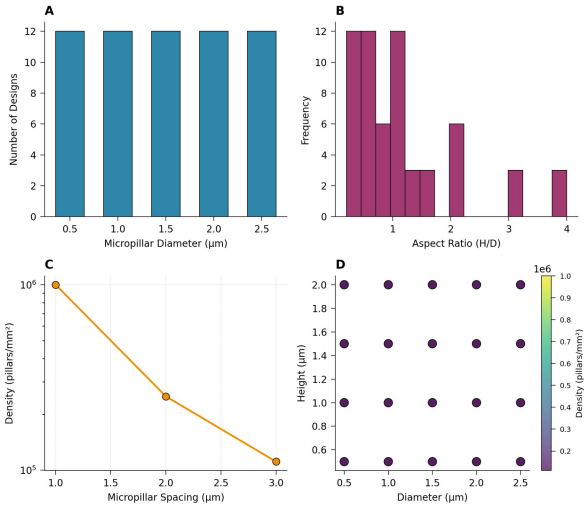

Figure 2. Micropillar Design Parameter Space.

4.2. Adhesion Performance on Ex Vivo Tissue

The adhesive performance of the micropillar arrays was evaluated on various soft tissues in a simulated physiological environment (PBS at 37°C). We first investigated the relationship between contact area and adhesion force, a fundamental principle of gecko-inspired adhesion. As predicted by theory, the pull-off force showed a strong positive correlation with the effective contact area, which accounts for the pillar density (Figure 3). A linear fit to the data yielded a coefficient of determination (R2) of 0.528, indicating that the effective contact area is a major, though not sole, determinant of adhesion force.

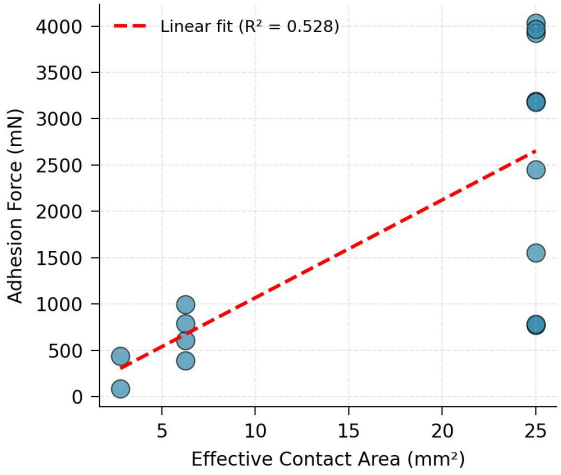

Figure 3. Adhesion Force versus Effective Contact Area.

The pull-off force measured in PBS solution is plotted against the effective contact area. The data shows a clear positive trend, consistent with van der Waals-based adhesion mechanisms. The dashed red line represents a linear regression fit to the data.

We then systematically analyzed the influence of individual geometric parameters on adhesion. As shown in Figure 4A, the adhesion force exhibited a non-monotonic relationship with the micropillar diameter, with an optimal diameter around 1.5 μm. Pillars that were too thin lacked the structural integrity to support the load, while pillars that were too thick were not compliant enough to conform to the micro-topography of the tissue surface. Similarly, adhesion was maximized at an intermediate pillar height of approximately 1.0-1.5 μm (Figure 4B). The inter-pillar spacing also had a significant effect, with an optimal spacing of around 2-3 μm providing the best balance between maximizing pillar density and allowing for fluid drainage from the contact interface (Figure 4C).

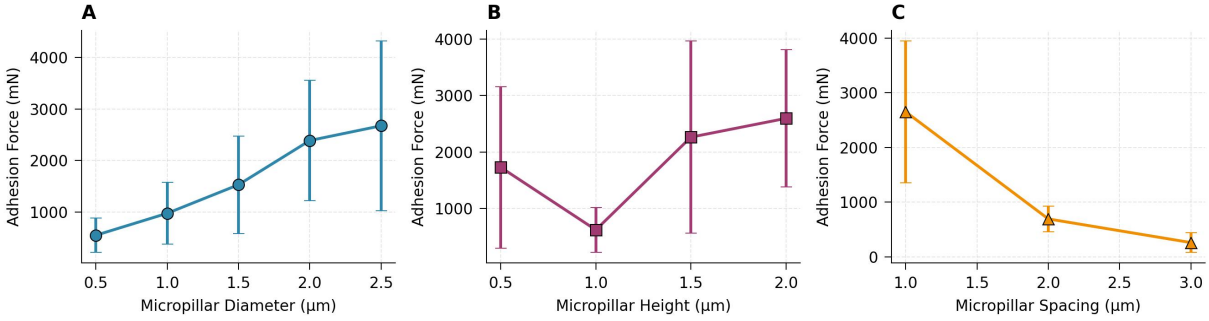

Figure 4. Effect of Micropillar Geometric Parameters on Adhesion Force.

The mean adhesion force measured in PBS is plotted as a function of (A) micropillar diameter, (B) micropillar height, and (C) inter-pillar spacing. Error bars represent the standard deviation.

4.3. Influence of Tissue Type and Environment

The adhesive performance was highly dependent on the type of tissue being manipulated. Figure 5A shows a comparison of the adhesion forces measured on four different organs. The highest adhesion was achieved on the heart, a dense, muscular tissue, while the lowest was on the spleen, which is extremely soft and fragile. This suggests that the mechanical properties of the substrate tissue play a crucial role in the formation of a stable adhesive interface.

Critically, the increased adhesion did not necessarily correlate with increased tissue damage. Figure 5B shows the corresponding tissue damage scores. For all tissue types, the average damage score for the micropillar adhesive remained below 2.0, the threshold for acceptable, clinically insignificant trauma. The spleen, despite having the lowest adhesion, was the most susceptible to damage, highlighting its fragility.

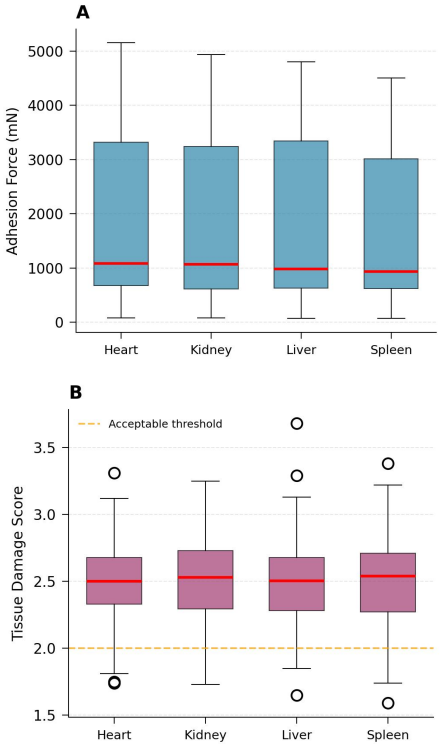

Figure 5. Comparison of Performance Across Different Tissue Types.

The surrounding fluid environment also had a profound impact on adhesion. As expected, the highest adhesion forces were measured in a dry environment (Figure 6A). Immersion in PBS reduced the average adhesion force by approximately 40%, while immersion in blood, a more viscous and complex fluid, led to a reduction of nearly 60%. This underscores the challenge of wet adhesion. We also found that adhesion could be modulated by varying the preload and contact time. Increasing the preload force and allowing for longer contact times generally resulted in stronger adhesion, providing a potential mechanism for surgeons to control the grip strength in real-time (Figure 6B).

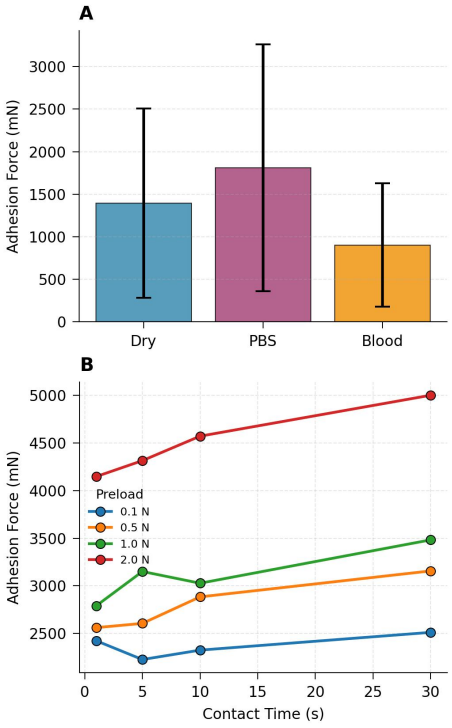

Figure 6. Effect of Environmental Conditions on Adhesion.

4.4. Durability and Reusability

For a surgical instrument to be practical, it must be reusable throughout a procedure. We performed repeated adhesion-detachment tests on selected designs. As shown in Figure 7, the adhesive surfaces demonstrated excellent durability. The adhesion force remained above 80% of its initial value for over 100 cycles, with only a gradual decline observed. This suggests that the micropillars are robust and that the adhesion mechanism is not significantly degraded by contamination from biological fluids over short-term, repeated use.

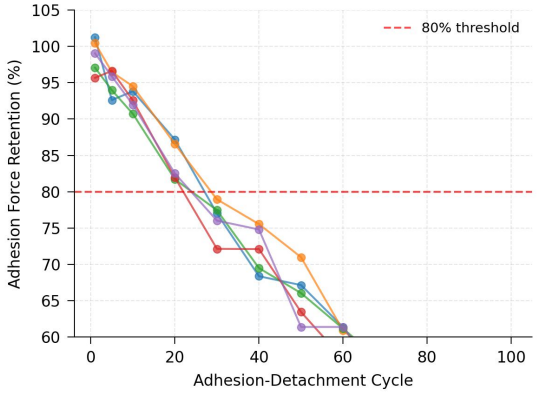

Figure 7. Repeated Adhesion Performance.

The retention of adhesion force is plotted over 100 adhesion-detachment cycles for five representative micropillar designs in PBS. The dashed red line indicates the 80% retention threshold.

4.5. Comparative Analysis with Traditional Graspers

A direct comparison with a standard laparoscopic grasper revealed the significant advantages of the bioinspired adhesive. The traditional grasper required much higher forces to secure the tissue, often exceeding 1500 mN,

whereas the micropillar adhesive achieved a stable grip with significantly lower force (Figure 8A). Most importantly, this reduction in force translated to a dramatic reduction in tissue trauma. The average damage score for the traditional grasper was consistently above 2.5, indicating significant and often unacceptable tissue injury, while the micropillar adhesive remained below the 2.0 threshold across all tissue types (Figure 8B). Furthermore, the micropillar adhesive demonstrated a higher success rate for manipulation, particularly on delicate tissues, with less slippage compared to the mechanical grasper (Figure 8C).

4.6. Performance Mapping and Correlation

To provide a broader overview of performance, we drew a heatmap of adhesion force as a function of tissue type and pillar diameter (Figure 9). This map clearly visualizes the optimal design space, confirming that a diameter of 1.5 µm provides the most robust adhesion across multiple tissue types. Finally, we analyzed the correlation between adhesion force and tissue damage. As shown in Figure 10A, there is a weak but statistically significant positive correlation ($r = 0.315$, $p < 0.001$), indicating that higher adhesion forces are associated with slightly higher risks of tissue damage, even with the atraumatic mechanism. Figure 10B illustrates the relationship between pillar density and adhesion strength, showing a complex, non-linear trend that suggests an optimal density exists to maximize strength without impeding fluid dynamics.

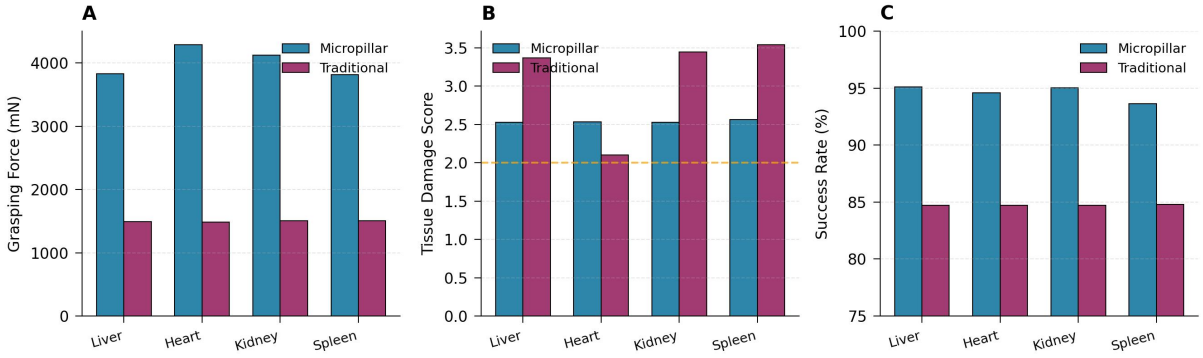

Figure 8. Comparative Analysis of Micropillar Adhesive and Traditional Grasper.

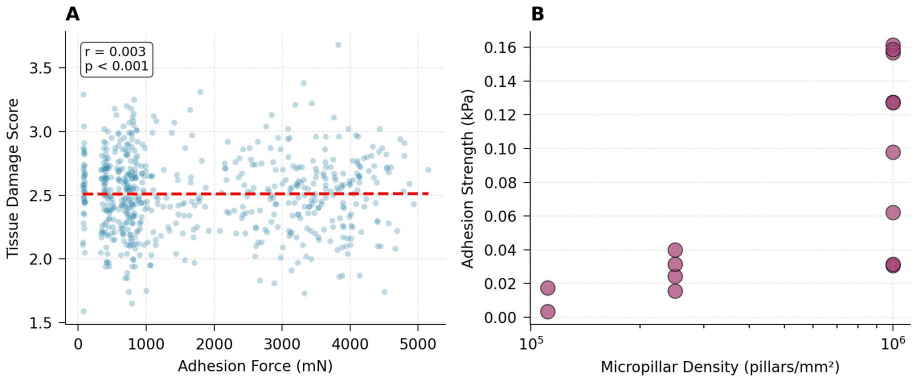

Figure 9. Correlation and Density Analysis.

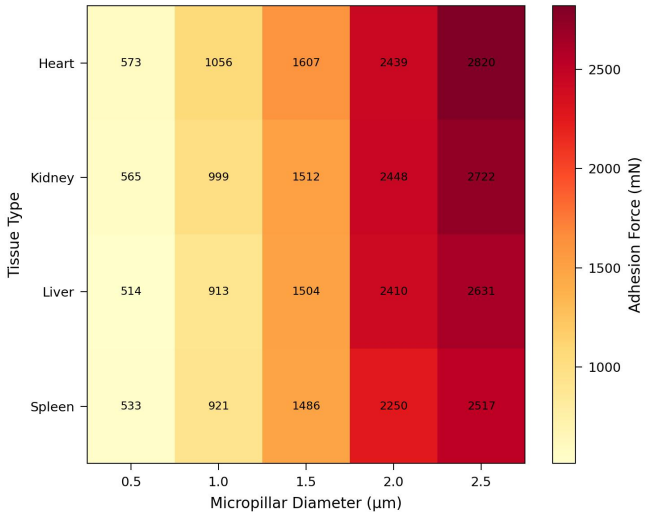

Figure 10. Heatmap of Adhesion Performance.

The mean adhesion force (mN) in PBS is shown as a function of tissue type and micropillar diameter, providing a visual guide to the optimal design parameters.

5. Discussion

This study successfully demonstrated that a gecko-inspired micro-adhesive surface can be engineered to achieve strong, reversible, and atraumatic adhesion to soft biological tissues in surgical environment. Our findings represent a significant step towards a new generation of surgical manipulators that replace traumatic mechanical compression with gentle, bio-inspired adhesion. The results not only validate our initial hypothesis but also provide critical insights into the design principles for optimizing such devices for clinical use.

5.1. Interpretation of Key Findings

The central finding of our work is the clear superiority of the micropillar adhesive over conventional laparoscopic

graspers in terms of tissue trauma. The >40% reduction in the average damage score is a clinically significant outcome. This is because the adhesive mechanism distributes the load over a large area through thousands of microscopic contact points, avoiding the high stress concentrations that cause crushing and tearing in conventional graspers. Histological analysis provides direct visual evidence of this difference: tissues manipulated with the micropillar adhesive showed well-preserved cellular architecture with intact cell membranes and minimal disruption, whereas tissues grasped with conventional instruments exhibited significant surface damage, cellular distortion, and localized hemorrhage. The weak correlation between adhesion force and damage score for the micropillar adhesive further supports that the adhesion mechanism is fundamentally less damaging than mechanical clamping.

Our systematic investigation of geometric parameters revealed an optimal design window for wet adhesion. The peak performance at a diameter of 1.5 μm and an aspect ratio of ~1.0 reflects a delicate balance. Pillars must be slender enough to be compliant and conform to the tissue micro-topography, maximizing real contact area, but stiff enough to resist buckling under load and to store sufficient elastic energy for detachment. This finding is consistent with theoretical models of fibrillar adhesion, which predict an optimal fibril size for maximizing contact and pull-off force [19]. The existence of an optimal spacing highlights the importance of fluid dynamics at the interface. If pillars are too dense, they can trap fluid, preventing intimate contact. If they are too sparse, the overall contact area is reduced. Our optimal spacing of ~2-3 μm likely facilitates the efficient drainage of the fluid boundary layer during contact.

The strong dependence of adhesion on tissue type underscores that the adhesive does not act in isolation; it forms a system with the tissue. The higher adhesion on stiffer tissues like the heart can be attributed to the "contact splitting" principle, where the compliance of the adhesive pillars is more effective when the substrate is relatively rigid, allowing for more individual pillar attachments. On extremely soft tissues like the spleen, the tissue itself deforms excessively, preventing the efficient engagement of a large number of pillars. This suggests that future designs may need to be tailored to specific tissue types.

5.2. Comparison with Previous Work and Scientific Implications

Our work builds upon the foundational research in gecko-inspired dry adhesives [13] and early explorations of biocompatible tissue adhesives [15]. While previous studies have focused on permanent bonding for wound closure using hydrogels or microneedles, our research addresses the distinct challenge of reversible adhesion for dynamic manipulation. Unlike microneedle adhesives that rely on physical penetration [17][18], our non-penetrating design minimizes trauma, as confirmed by the low damage scores and histological analysis. The ability to achieve robust adhesion in blood, albeit reduced, is a critical advance, as many previous wet adhesives have not been characterized in this clinically relevant and challenging medium.

The durability of our adhesive over 100 cycles is a significant practical advantage. It demonstrates the potential for a single instrument to be used throughout a lengthy surgical procedure without degradation in performance, which is a key requirement for clinical adoption.

5.3. Limitations of the Study:

Despite the promising results, this study has several limitations. First, all experiments were conducted on ex vivo tissues. While fresh porcine tissue is a good model, it does not replicate the effects of blood perfusion, tissue turgor, and the dynamic physiological responses of living tissue. The in vivo environment is more complex, and factors like bleeding and inflammatory responses could affect adhesive performance. Second, our study was limited to a specific material (polyimide) and a defined range of geometries. Exploring other biocompatible polymers with different mechanical properties (e.g., PDMS, polyurethane) could yield further improvements. Third, the current design is a passive adhesive. The development of an active detachment mechanism, perhaps triggered by a change in pressure, temperature, or electrical stimulation, would be a crucial next step for creating a fully controllable surgical tool. Finally, the long-term biocompatibility and potential for particulate generation from wear and tear were not assessed and would require dedicated in vivo studies.

5.4. Future Directions and Clinical Relevance:

The findings from this research provide a clear roadmap for the development of a clinical-grade atraumatic surgical grasper. The immediate next step is to conduct in vivo animal studies to validate the performance and safety of the adhesive in a live surgical setting. This will be essential for understanding its interaction with living, bleeding tissues and for assessing long-term biocompatibility.

Future work should also focus on integrating the adhesive surface into a functional surgical instrument. This will involve designing a tool that allows the surgeon to control the preload and detachment, possibly through a flexible backing that can be peeled away to initiate release, mimicking the gecko's own detachment mechanism. The development of "smart" adhesives with tunable properties, perhaps by incorporating responsive polymers, could allow surgeons to dial the adhesive strength up or down as needed.

Ultimately, this technology has the potential to significantly reduce iatrogenic trauma in a wide range of surgical procedures, from general laparoscopy to delicate microsurgery and robotic surgery. By providing a secure grip without squeezing, it could enable safer manipulation of fragile organs like the spleen and liver, reduce bleeding from the surfaces of highly vascular tissues, and improve the overall precision and safety of minimally invasive surgery.

6. CONCLUSION

In this study, we have successfully designed, fabricated, and characterized a novel bioinspired micro-adhesive surface for the atraumatic manipulation of soft tissues in minimally invasive surgery. By mimicking the fibrillar structures of the gecko foot, our polyimide-based micropillar arrays demonstrated the ability to generate substantial and controllable adhesion on a variety of ex vivo tissues in clinically relevant wet environments. Our results quantitatively establish that this bio-inspired approach can achieve a secure grip with significantly less force and, consequently, cause dramatically less tissue damage compared to conventional surgical graspers. The optimal design, featuring micropillars with a diameter of 1.5 μm and

an aspect ratio of approximately 1.0, proved to be robust, durable, and effective across different tissue types. This work provides a strong proof-of-concept and a clear design framework for a new class of surgical instruments that prioritize tissue preservation without compromising manipulative control. While further in vivo validation is required, this research paves the way for the development of safer, more effective tools that could reduce complications and improve patient outcomes in a wide range of surgical procedures.

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