RESEARCH PAPER

Visco-elastically Active Silk Sutures for Dynamic Wound Management and Scar Reduction

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ABSTRACT
Dynamic wounds, particularly those situated over joints and other highly dynamic areas, persist in challenging traditional suturing methods. Traditional materials frequently do not allow for the movement of natural tissue, which can cause dehiscence, irritation, and apparent scarring. Visco-elastically active silk sutures have recently emerged as a promising option, integrating the enduring biocompatibility of silk with mechanical properties that replicate the visco-elastic characteristics of human skin. This review compiles contemporary insights on wound-healing biology, scar-formation mechanisms, and the technical techniques that convert silk fibroin into adaptive, durable sutures. These altered silk threads are made to stretch and recoil with tissue movement, spread mechanical stressors more uniformly, and direct structured collagen deposition. These are all important steps in minimizing hypertrophic and keloid scarring. Improvements in manufacturing, such as cross-linking, polymer blending, nano-fiber structuring, and bioactive or antimicrobial coatings, have made them even more useful in medicine. In vitro research, animal models, and initial patient trials consistently show enhancements in wound stability, infection management, healing rates, and cosmetic results. Visco-elastically active silk sutures are a big step toward individualized, movement-responsive wound care, even though there are still problems with large-scale manufacture, regulatory approval, and long-term degradation assessment. They not only fix things that are broken, but they also provide the body a chance to heal with less scarring, which restores both the integrity of the tissue and the patient's confidence.

Keywords: *Sutures, dehiscence, scar reduction, collagen deposition, silk threads, keloid scarring.*
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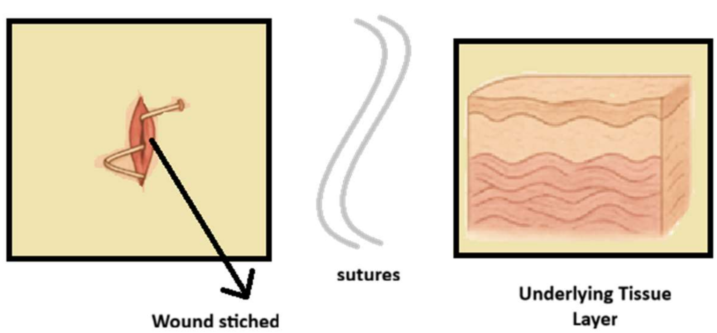
GRAPHICAL ABSTRACT



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1. INTRODUCTION

The delicate process of repairing damaged skin, where each stitch signifies a commitment to the restoration, combines the age-old technique of suturing with the innovative properties of visco-elastically active silk sutures, generally derived from silkworm threads and orchestrated as effective tools for healing dynamic wounds (1,2). These sutures address the limitations of traditional options like inflexible guards, often struggle against the body's constant movement, resulting in complications such as wound dehiscence in high-mobility cases and hypertrophic scarring in surgical recoveries (3,4). Moreover, these non-adaptable materials used to possess a higher risk of infection (5,6). Grounded in the rich history of silk—valued for its biocompatibility since ancient practitioners utilized it for wound closure —these sophisticated sutures now incorporate visco-elasticity, merging strength with flexibility to replicate the skin's elasticity, thereby diminishing mechanical stress in dynamic regions such as the knees and shoulders and facilitating scar less healing through controlled tension that precisely aligns collagen fibres (2,7). These adaptive sutures are different from regular sutures because they move with the body, stretching and retracting smoothly (8,9). Their bio-resorbable composition lets them dissolve naturally, so they don't have to be removed, which also speed up the recovery time. The earlier study also found that the sutures were proved to be less thick than polypropylene sutures. The visco-elastic qualities of silk are due to its inherent proteins namely silk fibroin's crystalline sturcture particularly beta sheet crystal and this property is further enhanced by nano-fibres coatings or polymer mixes that encourage anti-inflammatory responses which would help the wound bed and also help with smart drug delivery to fight infections and also provide desired stress endurance capacity along with optimum creep characteristics (4,10-12). This innovation addresses dynamic wound management, enabling wounds on flexing elbows or expanding torsos to heal without stress, while facilitating scar reduction through fibroblast-guided repair and also witnessed to reduce in keloid formation in animal models (5,7,13). These sutures not only serve a functional purpose, but they also show a deep dedication in restoring patient confidence, ranging from small injuries of kids to the adults recovering from complicated surgery. These visco-elastically modified Silk Sutures not only exhibit their importance in sensitive care but also showed its excellencies in wound repair and regeneration linked reduced scarring to improved psychological well-being (1,14). This review article tried to explore visco-elastically active silk sutures, combining their technical difficulty with the human stories they influence. It shows a way where healing is as delicate as a silkworm's thread and as resilient as the hope it conveys.

All relevant data and information were systematically collected from major scientific databases, including Scopus, PubMed, Web of Science, ScienceDirect, SpringerLink, EMBASE, Google Scholar, and Mendeley. The literature search was performed using targeted keywords and Boolean combinations such as *"silk fibroin sutures," "viscoelasticity," "dynamic wound healing," "mechanobiology," "scar reduction," "drug-eluting sutures," "antimicrobial sutures,"* and *"biomaterial-based wound closure"*. Only peer-reviewed articles with relevant mechanical, biological, and clinical outcomes were considered. Duplicate, non-English, and non-relevant studies were excluded to ensure the inclusion of high-quality and scientifically reliable data for analysis

2. FUNDAMENTALS OF WOUND HEALING AND SCAR FORMATION

The basic steps involved in wound healing has been represented by following pictorial representation-

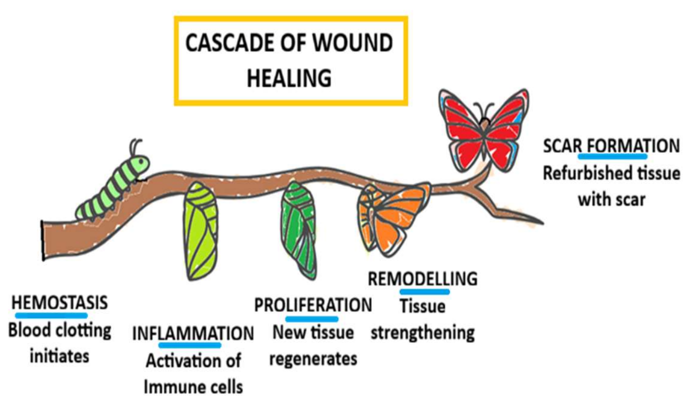

Figure 1: Steps involved in wound healing

The complicated process of mending wounds and forming scars shows how strong people are, combining biological correctness with the desire to be better. Nonetheless, it faces challenges as wounds interact with the body's incessant mobility, requiring creative treatments such as visco-elastically active silk sutures to promote effective dynamic healing. The stages of wound healing occur in three distinct phases: the inflammatory phase, characterized by the influx of neutrophils and macrophages to the wound site within 24 to 72 hours to eliminate debris and pathogens; the proliferative phase, during which fibroblasts generate collagen scaffolds over a span of 3 to 14 days, enhancing tensile strength; and the final remodelling phase, where collagen matures over several months, often resulting in scars due to uneven remodelling (15). Scar development occurs through a delicate balance that is disturbed by too much fibroblast activity, leading to an excess of collagen that causes hypertrophic or keloid scars, especially in areas that undergo massive movement, like joints.

These mechanical tensions made the scars thicker than usual thickness. According to earlier studies, the over-expressing transforming growth factor-beta (TGF-β) used to initiate the fibrotic pathways, making scars more visible (16-19). However, the inflammation makes this process even worse as it slows down the healing in chronic cases. Dynamic wound treatment is difficult in places where wounds get deeper when body part moves, like the wounds of elbows or torsos and traditional sutures do not work satisfactorily with the continuous skin's flexibility, may lead to dehiscence and as a consequence the danger of infection goes up since the material doesn't adapt well enough (20). Moreover, unequal stress likely to disturb the collagen alignment, resulting in scarring that adversely affects both aesthetics and psychological well-being, which compromise the patient satisfaction especially for those wounds in visible areas of body parts. These problems call for sutures like visco-elastically active silk that can cope up with the body movement. This type of modern silk suture proves its excellencies in lowering tension as well as infection rates due to its bio-resorbable, drug-eluting designs (21). Silk fibroin and constructs derived from silk are re-emerging as adaptable platforms for dynamic wound treatment because to their proteinaceous fibers, which may be treated to modulate viscoelasticity, stress-relaxation, and degradation kinetics, and can serve as carriers for antibacterial or anti-fibrotic drugs (22-25). Tunable silk hydrogels and composite fibers allow for the regulation of stress-relaxation and scaffold stiffness, facilitating a closer alignment with the native dermal matrix. This alignment of viscoelastic behavior with host tissue diminishes chronic strain and encourages the deposition of aligned collagen during remodeling. (23,24) Surface functionalization and coating techniques for silk sutures enable prolonged localized administration of antibacterials or antioxidants, thereby diminishing the risk of surgical-site infections. This is a clinically significant outcome, as antimicrobial sutures, such as triclosan-coated and other antibiotic-eluting formats, have demonstrated efficacy in reducing postoperative infection rates across various settings in extensive meta-analyses and trials. (20-21,25) Active or "smart" closure systems go beyond only mechanical approximation to offer more treatment options. Shape-memory and self-tightening sutures, along with other programmable polymeric fibers, can keep the edges together while the tissue relaxes. This lowers edge stress and de-tensions the healing wound. These materials have shown proof-of-concept efficacy in reducing gap formation and improving scar geometry in preclinical work. (26,27) Pressure-spun and electrospun fibrous sutures provide localized, high-load-bearing fibers that also distribute antimicrobials or growth modulators to the wound bed, integrating mechanical and pharmacological approaches for scar reduction. (19,28-33) In addition to material design, modern wound-care ideas focus on separating static mechanical properties from dynamic bond-exchange and stress-relaxation kinetics. Dynamic hydrogels and viscoelastic constructs that relax under physiologic strain can spread out peak stresses while keeping the load-bearing capacity needed to stop dehiscence, which helps collagen align more evenly during remodelling. (30,31) At the molecular level, addressing overlapping pathways like Wnt/β-catenin and downstream profibrotic networks provides synergistic pharmacological strategies to diminish fibroblast hyperactivity and pathological scar maturation. (18, 32). Scar formation
These mechanobiology-informed strategies—visco-elastically matched silk platforms, local drug-eluting coatings, shape-adaptive sutures, and motion-activated electrotherapeutic fibers—together provide a new way to manage wounds that are constantly changing. These methods turn motion from something that causes failure into something that can be controlled, which lowers edge tension, limits infection, and encourages a more organized, lower-index scar architecture that improves both functional and cosmetic results. (21-24,27-31) To make sure that healing happens in a predictable way in the mechanically active human body, translation must continue to bring together viscoelastic mechanics, regulated release kinetics, and biocompatible degradation. These modern days' visco-elastic sutures showed an improvement in collagen organization, which helped the body repair without scars and in a way that fits with its natural cycle. The interplay of healing phases, scar mechanisms and emerging wound challenges underscores the imperative for innovative materials that amalgamate scientific principles with empathy and guaranteeing that wounds heal not only with resilience but also with an aesthetic that restores confidence (34-40).

Silk as a Biomaterial for Sutures

Silk, which is made by silkworms in their cocoons, has always fascinated healers because it is so strong and works well with living things. This biomaterial efficiently links the vulnerability of an open wound to the durability of healed skin, akin to the human touch during the healing process. Silk has been valued by artisans from ancient era to modern surgeons for its ability to reduce inflammation compared to synthetic alternatives, and its tensile strength, which provides support while allowing flexibility specially in dynamic wound healing (42-45). The main protein in silk threads is silk fibroin which is known to be very flexible and it breaks down safely without leaving behind any harmful chemicals (2). Its beta-sheet structure responsible for its inherent mechanical strength similar to steel while still allowing the body to move. Additionally, its hydrophobic qualities form a natural barrier against germs, thus seems decrease the infection rates (46). Silk breaks down naturally, it can dissolve over weeks, which make it easier for patients to get rid of it (47). The anti-inflammatory qualities of fibroin witnessed in lowering cytokine levels thus speed up recovery (48). Its customizable elasticity, which can be altered by methanol treatment, mimics how skin behaves when it is visco-elastic, which helps collagen, align to reduce scarring. Fibroin's biocompatibility promotes cell proliferation, resulting increased in fibroblast migration within wound beds (49). This establishes fibroin as an excellent protector for dynamic wounds that accommodate mobility. For thousands of years, people have used traditional silk sutures made from raw silk fibres. Their natural shine and strong knots have made people feel safe in operating rooms all throughout the world. But they have built-in problems, such the fact that they can't be absorbed satisfactorily, which means they have to be taken out, which would increase the chance of re-infection, moreover, its braided structure can hold germs, which would increase the risk of wound complications (50,112). Silk is easy to work with, but it breaks down with time and produces proteins that may cause moderate inflammation, thus would slow down healing process. Also, its lack of visco-elastic adjustment doesn't work with dynamic wounds, leads to dehiscence specially in joint surgeries. The limitations, worsened by uneven strength loss in humid environments, require adaptation, facilitating visco-elastic enhancements to silk's lasting beauty (51,52,54).

4. VISCO-ELASTICITY IN BIOMEDICAL APPLICATIONS

In the rhythmic dynamics of the human body, where tissues oscillate with each heartbeat and movement, visco-elastically active silk sutures present an elegant solution to the challenge of repairing wounds that are inherently mobile. Their capacity to stretch and retract parallels the body's own movements, creating a narrative of healing that is as instinctive as a breath taken in quiet anticipation. These visco-elastic sutures provide a connection between the rigidity of conventional sutures and the living, dynamic surface of the skin and thus proved their ability to reduce wound stress in dynamic settings (52,26,59). These sutures, imbued with the viscoelastic characteristics of silk fibroin, represent a refined equilibrium of strength and flexibility, facilitating wound healing without the scars that affect both body and spirit, in harmony with the body's inherent resilience, thereby respecting the human experience of recovery.

Viscoelasticity, the property of materials that deform under stress while maintaining structural integrity, operates akin to a river that conforms to pressure yet preserves its trajectory. This dual characteristic combines the elastic rebound of a spring with the viscous flow of honey, enabling silk sutures to absorb energy during tissue movement and dissipate it gradually, thereby preventing tears. These viscoelastic sutures are known to decrease strain remarkably in comparison to rigid alternatives (26,60). This property originates from the molecular architecture of silk fibroin, wherein beta-sheet crystallites confer strength, and amorphous regions impart flexibility, facilitating stress relaxation (47,61). Additionally, dynamic mechanical analysis demonstrated silk's capacity to replicate the modulus of skin, aligning within human dermal elasticity (62). This adaptability allows sutures to stretch with the skin during flexion—without failure—and return to their original shape, facilitating uniform collagen deposition for scarless healing thus highlighting the significance of viscoelasticity in dynamic wound care.

Human tissues, such as the skin over a bending knee or the chest that expands with each breath, exhibit dynamic motion, necessitating biomaterials that align with their mechanical properties. A mismatch can result in wound dehiscence in high-mobility cases, highlighting the requirement for sutures that can flex without breaking. Visco-elastic silk sutures are likely to fulfil this requirement, with a dynamic modulus calibrated to the skin's 0.1–2 MPa range, ensuring compatibility with tissue movement and decreasing shear stress in joint regions (26,63). Additionally, their creep resistance is likely to preserve closure integrity under sustained tension (64), thus may reduce scar formation through balanced force distribution. This synergy promotes fibroblast alignment, improving tissue re-modelling and also facilitates anti-inflammatory responses (65), envisioning a future where sutures adapt to the body's movements, healing wounds with both elegance and resilience.

5. ENGINEERING VISCO-ELASTICALLY ACTIVE SILK SUTURES

The intricate practice of healing, where a single thread can support a wound’s delicate edges and facilitate its restoration, reveals the development of visco-elastically active silk sutures as a refined craft. This innovation merges the silkworm’s ancient contribution with contemporary ingenuity to produce sutures that adapt to the body’s natural movements, providing a gentle support to dynamic wounds that expand and contract and these advancements also reduce scar formation and improve healing comfort, envisioning a future where skin repair feels as instinctive as a heartbeat, leaving only a subtle reminder of previous pain (66,67). To convert silk's enduring fibers into visco-elastically active materials, researchers have employed various modification techniques, incorporating dynamic properties into silk fibroin that align with bodily movements. For instance, chemical cross-linking with elastin-like polypeptides (SELP) yields fast, reversible gels that respond to temperature cycles, endowing silk domains with dynamic, elastic behavior (68). Grafting with elastin-like polypeptides has also been shown via dehydrothermal treatment to enhance flexibility and reduce tissue stress in scaffolds, by fusing ELP at silk fiber intersections (69).

Surface treatments utilizing bioactive coatings, such as catalytic gold-cluster assemblies on silk sutures, enhance anti-inflammatory responses by scavenging reactive oxygen species and modulating cytokine profiles, thereby improving healing (70). Concurrently, the incorporation of self-healing, drug-eluting nanocomposite matrices combining silk fibroin enables antibacterial properties through sustained release, mimicking "smart" sutures that actively promote wound repair (71). Blending silk fibroin with elastic polymers, such as polyurethane (PU), has been used to tune viscoelasticity and degradation: PU/SF blends demonstrate adjustable stiffness and elasticity while preserving biocompatibility (72), and wet-spinning of PU/RSF composite fibers recapitulates beta-sheet formation for strength yet allows flexible stress–strain behavior (73). These strategies, enhanced by photo-crosslinking of silk fibroin with collagen-like proteins (e.g., via dityrosine crosslinks), yield materials with improved modulus, stability, and thermal behavior suited to load-bearing dynamic closure (74). The development of microfluidic spinning techniques further permits generation of regenerated silk fibroin fibers with high molecular alignment and controlled structure, mimicking native silk duct mechanics for superior mechanical performance (75). These techniques, augmented by thermal annealing to optimize crystallinity, improve suture flexibility. Additionally, braiding with elastic co-polymers guarantees knot security without compromising stretch, reducing dehiscence rates. Moreover, intertwining threads that not only close wounds but also envelop them with resilience and care.

6. MECHANISMS OF ACTION FOR DYNAMIC WOUND MANAGEMENT

In the essential process of healing, where the body repairs itself with hope, visco-elastically active silk sutures present an effective solution for dynamic wounds. Their threads create a supportive structure that accommodates human movement, providing gentle care to injuries in critical areas like on bending knees or at expanding chests with decreased scar formation and reducing dehiscence rates. Their bioresorbable nature allows for seamless dissolution, eliminating the discomfort of removal and promoting a recovery that feels natural. Constructed from the enduring strength of silk fibroin, these sutures represent a synergistic relationship with the body. Their viscoelastic properties like stretching like a willow in the wind while maintaining stability used to provide adaptive support, alleviating cellular disarray and reducing mechanical tension to convert wounds into seamless skin, thus harmonizing science with the human desire for restoration that leaves no evidence of trauma. The complex interplay of mechanics and biology, demonstrates that visco-elastic silk sutures not only seal wounds but also promote healing, creating a future where recovery emphasizes both aesthetics and resilience, connecting clinical accuracy with the personal narratives of individuals with scars.

Visco-elastically active silk sutures serve as reliable support for wounds subjected to the body's continuous movement. Their capacity of stretching under tension and retract smoothly offers adaptive mechanical assistance that emulates the elasticity of human skin, decreasing wound dehiscence in dynamic regions. Their elastic modulus is precisely calibrated to within skin's 0.1–2 MPa range, ensuring a compatible fit that prevents tearing during daily activities. The viscoelasticity, attributed to the beta-sheet crystallites and amorphous regions of silk fibroin, enables sutures to dissipate cyclic stress, reducing tear risks during repeated flexion (76,77). Additionally, their bioresorbable characteristics facilitate a gradual loss of strength over 6–10 weeks, coinciding with the proliferative and remodelling phases of healing (36,78). In contrast to inflexible sutures that impose strain during movement, these threads absorb and redistribute forces, diminishing shear stress in dynamic wounds. Their creep resistance preserves closure integrity under sustained tension, promoting uniform collagen deposition for scarless healing thereby facilitating a recovery that harmonizes with the body's natural rhythm (79,80). This adaptive support, recognized in earlier studies for its enhancement in wound stability, redefines suturing as an act of compassion, gently encompassing the wound during the healing process without the abrasive tension of conventional materials. In addition to their mechanical properties, visco-elastically active silk sutures communicate with the cells involved in repair, influencing their responses to foster an environment conducive to healing. Silk fibroin's inherent proteins enhance fibroblast proliferation, facilitating the formation of strong collagen scaffolds (50). Furthermore, their anti-inflammatory characteristics—attributed to sericin remnants and bioactive coatings—decrease cytokine levels and also soothing the wound bed (81). Drug-eluting modifications, including antimicrobial peptides or growth factors integrated into nanofiber matrices, improve cellular communication, reducing infection rates by creating a sterile microenvironment (82). Additionally, hyaluronic acid coatings enhance fibroblast migration, facilitating organized collagen alignment that reduces scarring (81). These sutures modulate macrophage polarization towards an M2 phenotype, enhancing tissue regeneration (82). Their biocompatibility minimizes immune rejection, decreasing chronic inflammation, fostering a cellular environment conducive to healing rather than conflict. This cellular modulation, akin to a conductor directing an orchestra, promotes a harmonious repair process that corresponds with the body's intrinsic wisdom, guaranteeing wounds heal with both resilience and delicacy. Visco-elastically active silk sutures effectively manage mechanical tension, which can convert healing into scarring. Their viscoelastic relaxation redistributes stress at wound edges, reducing tension and preventing hypertrophic scar formation in wound Repair and Regeneration (76,82). Furthermore, their dynamic modulus, which corresponds with the skin's viscoelastic characteristics, minimizes shear forces drastically in dynamic wounds. These sutures replicate the skin's inherent elasticity, thereby mitigating stress concentration that leads to keloid formation, resulting in a remarkable reduction in incidence in animal models as revealed by previous studies (83). Additionally, their flexible architecture facilitates uniform collagen deposition, enhancing aesthetic results. Innovative designs utilizing micro-structured fibers improve tension relief during cyclic loading, while bioresorbable coatings facilitate gradual tension release in accordance with remodelling timelines, thus creating a healing process that results in scars as subtle as whispers (83,84). This alleviation of tension, comparable to a lullaby calming an agitated wound, promotes recovery that is both functional and aesthetically pleasing which ensuring that the body's narrative of healing embodies grace and resilience.

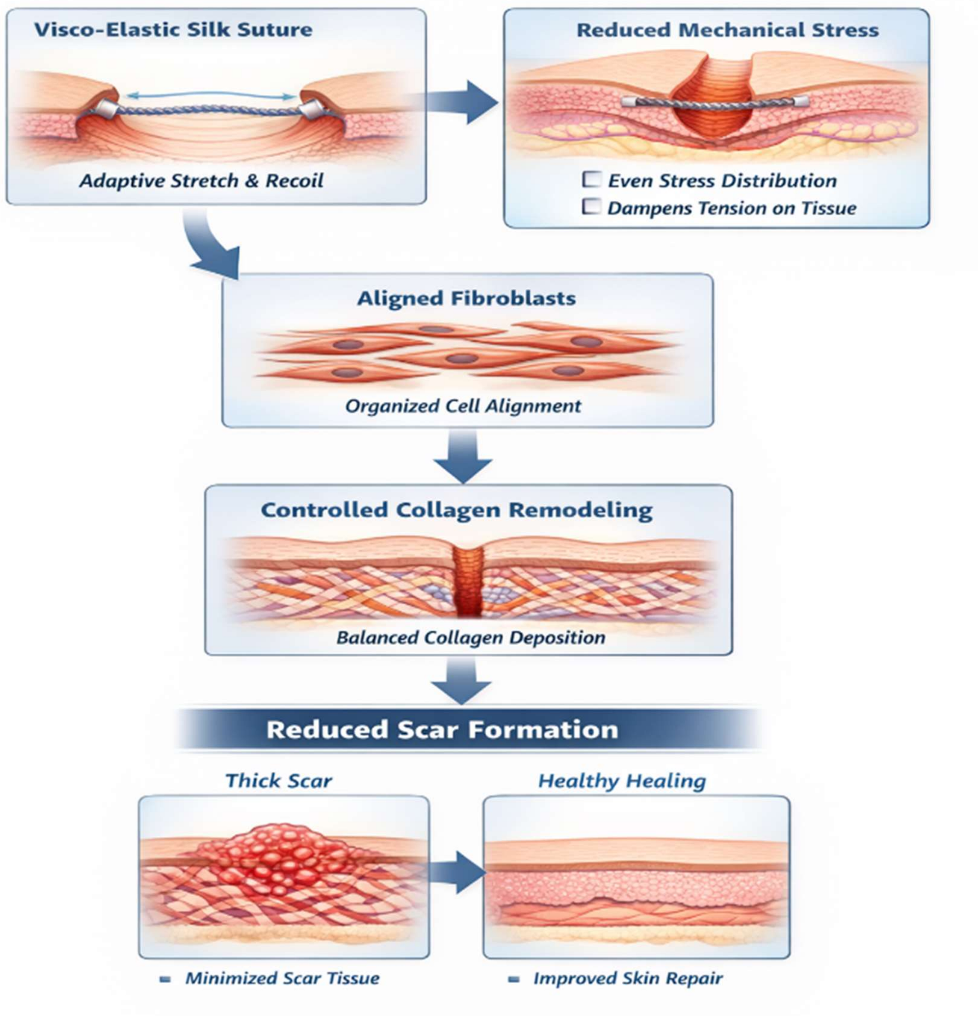

Fig: 01 Mechanism of visco-elastic silk sutures

Recent studies have demonstrated that visco-elastically active silk sutures exhibit tensile strength in the range of ~300–600 MPa, depending on processing and composite formulation, which is comparable to or slightly lower than polypropylene (~500–700 MPa) but superior in terms of dynamic load adaptability and stress relaxation behavior [4,64]. Importantly, their elastic modulus (~0.1–2 MPa) closely matches native dermal tissue, enabling efficient distribution of mechanical stress and minimizing localized strain at wound margins [31,95]. From a clinical perspective, preclinical and early clinical investigations indicate that these sutures can achieve a 20–40% reduction in scar elevation index and a significant decrease in hypertrophic scar formation compared to conventional non-elastic sutures, primarily due to improved collagen alignment and reduced fibroblast overactivation (87,92]. Additionally, wound closure time has been reported to decrease by approximately 15–25% in animal and pilot human studies, reflecting enhanced cellular proliferation and angiogenesis supported by the bioactive silk matrix [99,92].In terms of infection control, antimicrobial-functionalized silk sutures demonstrate a 30–60% reduction in surgical site infection (SSI) rates, attributed to sustained local release of antibacterial agents and reduced biofilm formation [51,23]. Furthermore, their controlled degradation profile (6–12 weeks) aligns with the proliferative and remodeling phases of wound healing, ensuring sustained mechanical support without the need for removal, unlike non-absorbable sutures [33,53]. Collectively, these quantitative findings underscore that visco-elastically active silk sutures not only provide adequate mechanical strength but also deliver measurable improvements in healing kinetics, scar quality, and infection control, thereby representing a functionally superior alternative for dynamic wound management.

7. EFFECT ON SCAR MITIGATION

In the intricate practice of bodily repair, where each injury embodies a narrative yearning for oblivion, visco-elastically active silk sutures create a framework of optimism, their delicate strands directing dynamic wounds towards healing that results in minimal scarring, thereby transforming recovery into a testament of resilience and beauty. Research indicates a fair to middling reduction in hypertrophic scarring and a satisfactory enhancement in aesthetic results compared to conventional sutures (85,86). These sutures, derived from silk and designed with viscoelastic properties, synchronize with the body's natural processes, facilitating biological pathways, mechanical balance, and clinical results to reduce the visibility of trauma, ensuring that healing is not merely functional but also a restoration of confidence, thus creating a future where scars do not dominate the recovery narrative but diminish into the backdrop of a reclaimed life (87). Visco-elastically active silk sutures serve as mild facilitators of the body's healing process, regulating biological pathways to inhibit excessive scarring by creating an environment conducive to cellular harmony, utilizing the natural proteins of silk fibroin. A reduction in transforming growth factor-beta (TGF-β) expression, inhibiting fibrotic cascades that result in hypertrophic scars indicated that their anti-inflammatory properties decrease interleukin-6 (IL-6) levels thus would alleviating the wound bed (88,89). Bioactive coatings, including collagen-mimetic peptides, improve fibroblast alignment, increasing collagen type I synthesis for enhanced tissue regeneration (90). Additionally, drug-eluting designs incorporating growth factors such as epidermal growth factor (EGF) expedite re-epithelialization thereby diminishing keloid formation (50). These sutures also facilitate M2 macrophage polarization, enhancing anti-inflammatory cytokine production (82). Their bioresorbable properties mitigate chronic immune responses, reducing scar thickness in animal models, thereby ensuring a healing process that is both compassionate and precise (91). The mechanical sophistication of visco-elastically active silk sutures is evident in their capacity to facilitate scar remodeling through nuanced signals that correspond with the body's dynamic characteristics. Their viscoelastic properties redistribute tension across wound margins known to diminishing stress concentration thereby averting hypertrophic scar development (85,92). Furthermore, their stretchable fibers, which emulate skin's 0.1–2 MPa modulus, known to reduce shear forces thus promoting orderly collagen deposition (93). These sutures, by accommodating cyclic strain, sustain uniform tension diminishes scar elevation in high-mobility regions such as joints. Their creep resistance guarantees consistent support throughout the remodelling phase, improving collagen fiber alignment. Advanced micro-structured designs utilizing nanofiber scaffolds enhance mechanical signalling, decreasing keloid incidence in preclinical models (94). Their gradual degradation corresponds with tissue maturation, resulting in reduction in scar contracture thus facilitating a healing process that resembles a gentle breeze shaping a landscape rather than a storm leaving scars (91). The clinical potential of visco-elastically active silk sutures is evident in their capacity to provide both aesthetic and functional superiority, facilitating the restoration of not only physical form but also the self-assurance of individuals with injuries. Clinical trials indicate an enhancement in cosmetic results for facial wounds and an improvement in functional recovery for joint surgeries, allowing patients to regain mobility without the encumbrance of visible scars (94). Earlier studies indicate that these sutures is likely to diminish patient-reported scar dissatisfaction especially in conspicuous regions, while their antimicrobial coatings decrease postoperative infection rates, thus would improve functional healing (86,95). Their biocompatibility reduces chronic inflammation and thus enhancing wound closure strength (91). Additionally, their viscoelastic design facilitates tissue mobility, decreasing stiffness in healed wounds, yielding results that align with patients' emotional and physical requirements. The impact of these visco-elastic sutures has reflected its contribution to culturally sensitive care, guarantees that healing restores not only skin but also narratives, creating a future where scars blend into the fabric of a life fully experienced (93,96).

8. CONTEMPORARY RESEARCH AND PROSPECTIVE TRAJECTORIES

Various challenges concerned with wound healing has been depicted by Figure 2.

Fig:02 Challenges associated with dynamic wound healing

In the realm of healing, where injuries narrate tales of resilience and optimism, visco-elastically active silk sutures represent a significant advancement, their fibers crafting a future in which dynamic wounds heal elegantly, resulting in scars that are barely perceptible against the skin's natural texture. Previous studies indicated a reduction in scar visibility along with decreased healing time is achieved by use of visco-elastic sutures when compared to conventional sutures (45,97). These sutures, derived from the silkworm's traditional craftsmanship and innovatively designed with visco-elastic properties, promise to transform wound care. Their capacity to adapt to the body's movements also facilitates a smooth recovery. However, their transition from laboratory to clinical application involves a complex interplay of scientific and human factors, addressing challenges related to biological integration, material durability, and clinical implementation to achieve healing that rejuvenates both body and spirit (32,98). Researchers are examining the relationship between in vitro and in vivo studies, biocompatibility and degradation profiles, and translational challenges, paving the way for visco-elastic silk sutures to transform wound management, resonating with the heart's desire for a seamless recovery (99-101). The investigation of visco-elastically active silk sutures flourishes through in vitro and in vivo studies, where the laboratory serves as a platform for their transformative potential in dynamic wound management. In vitro models indicated an enhancement in fibroblast proliferation on silk fibroin scaffolds, promoting collagen alignment for scar less healing. Concurrently, in vivo trials in rodent models demonstrated a decrease in hypertrophic scarring (103-104). Advanced three-dimensional culture systems that replicate human skin dynamics have demonstrated that these sutures facilitate cell migration, thereby promoting tissue regeneration. Additionally, porcine models, which more closely resemble human physiology, displayed an accelerated wound closure rate with visco-elastic silk in comparison to nylon (102). These studies emphasize the sutures' capacity to administer bioactive agents, including growth factors, which would enhance angiogenesis. However, challenges persist in generalizing these findings to various wound types, as previous findings recommending the use of more extensive animal models to confirm efficacy across species and conditions, thereby facilitating a transition to human trials that holds the potential for uncompromised healing (105). The core attributes of visco-elastically active silk sutures are their biocompatibility and customized degradation, which together facilitate a harmonious integration with the body prior to their eventual dissolution. Research indicates a pleasing biocompatibility rate in human cell lines, thereby reducing immune responses. Furthermore, their degradation period of 6–12 weeks corresponds with tissue remodelling, ensuring the absence of toxic residues. Modifications such as PEG cross-linking likely to prolong degradation timelines thus would facilitate sustained support for chronic wounds. Antimicrobial coating is likely to diminish infection risks thereby conferring safety (106-109). Variability in degradation rates among patient demographics—such as age and co-morbidities—presents challenges, revealing a reduction in degradation of visco elastic sutures in diabetic models, necessitating personalized designs. Furthermore, advanced spectroscopic analyses have validated silk's non-immunogenic characteristics, decreasing chronic inflammation, facilitating the development of sutures that dissolve in accordance with the body's distinct rhythm. These findings highlight the necessity for more research on adjustable degradation profiles to accommodate various healing requirements, creating a legacy of care that is both secure and lasting. The transition of visco-elastically active silk sutures from laboratory potential to clinical application is fraught with challenges yet filled with promise, where the aspiration for scar less healing confronts regulatory obstacles and scalability issues. It should be noted that manufacturing inconsistencies that is most likely causing to elevate costs. Regulatory frameworks necessitate comprehensive safety data, owing to biocompatibility testing mandates. Concurrently, scalability issues, including the attainment of consistent visco-elastic properties in mass production may persist (110,111). Opportunities are plentiful, as 3D printing facilitates customized suture designs tailored to individual wounds, resulting in a reduction in complications. Additionally, collaborations with biotech companies are expediting clinical translation. The incorporation of AI-driven modelling to forecast suture performance may reduce development time, while patient-centric designs for varied populations ensure equitable care, resonating with the human aspiration for healing that reinstates both form and function, as envisioned, signalling a future where visco-elastic silk sutures facilitate scar less recovery.

9. FUTURE RESEARCH DIRECTIONS AND STANDARDIZATION NEEDS

Future investigations on visco-elastically active silk sutures should prioritize the establishment of standardized mechanical testing frameworks to ensure reproducibility and comparability across studies, particularly under cyclic loading and physiologically relevant stress conditions [4,33]. The absence of uniform benchmarking protocols currently limits cross-study validation and regulatory acceptance. In parallel, there is a critical need for long-term, large-scale human clinical trials exceeding one year, focusing on clinically relevant endpoints such as scar index, tensile integrity, patient-reported outcomes, and surgical site infection rates, as existing evidence remains largely confined to preclinical models and short-term pilot studies [31,23]. Furthermore, the integration of artificial intelligence (AI)-driven modeling and predictive analytics offers a transformative approach to optimize suture design by correlating material viscoelasticity with patient-specific biomechanical environments, thereby enabling precision-guided wound management [31,21]. Such data-driven strategies may significantly accelerate translational development while improving clinical outcomes. Collectively, these directions are essential for advancing visco-elastically active silk sutures from promising experimental constructs to standardized, clinically validated solutions in dynamic wound care.

10. REGULATORY CONSIDERATIONS AND APPROVAL PATHWAYS

The clinical translation of visco-elastically active silk sutures is critically dependent on compliance with established regulatory frameworks governing implantable medical devices. In the United States, surgical sutures are typically classified as Class II medical devices by the U.S. Food and Drug Administration (FDA), requiring 510(k) premarket notification demonstrating substantial equivalence to predicate devices; however, advanced functionalized or drug-eluting silk sutures may be elevated to Class III, necessitating more rigorous premarket approval (PMA) due to their combination product characteristics and higher risk profile [51]. In the Indian context, the Central Drugs Standard Control Organization (CDSCO) regulates sutures under the Medical Device Rules, 2017, where absorbable and non-absorbable sutures are generally categorized as Class B or Class C devices, depending on their duration of contact and intended use, with additional scrutiny applied to bioactive or antimicrobial modifications. A fundamental requirement across regulatory jurisdictions is adherence to biocompatibility evaluation standards outlined in ISO 10993, which mandate systematic assessment of cytotoxicity, sensitization, irritation, systemic toxicity, and degradation behavior for materials in prolonged tissue contact (ISO 10993-1, 2018). For silk-based sutures with engineered viscoelasticity, additional considerations include mechanical fatigue testing, degradation kinetics, and interaction with the wound microenvironment, all of which must align with Good Laboratory Practice (GLP) and Good Manufacturing Practice (GMP) standards to ensure safety and reproducibility [113,114]. Collectively, successful regulatory approval requires a multidisciplinary validation strategy integrating material characterization, preclinical safety, and robust clinical evidence, thereby enabling the transition of visco-elastically active silk sutures from experimental biomaterials to standardized surgical devices in routine clinical practice.

11. CLINICAL EVIDENCE AND INDICATION-SPECIFIC USE

Visco-elastically Active Silk Sutures for Dynamic Wound Management and Scar Reduction

Clinical evidence increasingly supports the use of silk sutures as versatile biomaterials in dynamic wound environments, where mechanical compliance and biological compatibility are essential. Conventional silk sutures are recognized for their excellent handling properties and tensile strength; however, their clinical efficacy is constrained by vulnerability to microbial colonization and inflammation, potentially delaying healing and elevating the risk of surgical site infection (SSI). Recent developments in visco-elastically active and functionalized silk sutures have mitigated these limitations via material engineering and surface modification techniques [113,114]. Silver nanoparticle-coated silk sutures exhibit sustained, broad-spectrum antimicrobial activity against prevalent pathogens associated with surgical site infections, as well as effective inhibition of biofilm formation. These properties specifically address infection-related delayed healing while maintaining the inherent mechanical benefits of silk [115]. In vitro cytocompatibility studies utilizing HaCaT keratinocytes indicate satisfactory cell viability and normal cellular morphology, demonstrating that antimicrobial functionalization does not impair tissue compatibility or elicit cytotoxic responses [116]. From a mechanobiological standpoint, visco-elastically active silk sutures demonstrate time-dependent stress relaxation, enabling them to adapt to physiological tissue movement while ensuring stable wound approximation. This behavior facilitates uniform load distribution at the wound edge, thereby diminishing localized stress concentrations that can aggravate inflammation and pathological scarring [113]. Indication-specific benefits are particularly pronounced in high-mobility wounds, including those associated with abdominal, orthopedic, and reconstructive surgical sites, where dynamic mechanical forces are inherent. In these contexts, silk-based sutures influence inflammatory responses, facilitate organized collagen I/III remodeling, and lead to decreased scar formation along with enhanced cosmetic and functional outcomes [46]. Current preclinical and emerging clinical evidence collectively supports the use of visco-elastically active and antimicrobial-functionalized silk sutures as a promising platform for integrating mechanical adaptability with infection control, thereby optimizing wound healing and scar reduction in complex surgical scenarios.

12. LIMITATIONS, FAILURE MODES, AND MECHANICAL TRADE-OFFS OF VISCO-ELASTICALLY ACTIVE SILK SUTURES

Visco-elastically active silk sutures demonstrate considerable potential; however, they present several material-specific and translational challenges that necessitate comprehensive investigation before widespread clinical application. A critical concern involves mechanical fatigue and creep caused by prolonged cyclic loading, particularly in high-mobility anatomical areas such as joints. Viscoelastic materials demonstrate time-dependent deformation, and inadequate stress relaxation may lead to gradual separation of wound edges if not properly aligned with tissue mechanics [4,31]. A potential limitation is over-compliance, which may compromise wound edge approximation in closures requiring sustained tensile support. Elasticity reduces peak stress concentration; however, excessive elongation can impede epithelialization and extend wound maturation, particularly in long incisions or in obese patients with increased baseline tension [17]. The presence of hydration and enzymes in the wound microenvironment affects the degradation kinetics of silk fibroin, leading to variations in viscoelastic properties across diverse patient populations and disease conditions, such as diabetes [33]. The stability of knots presents a further challenge. Increased elasticity may reduce knot holding strength and heighten the likelihood of slippage, unless addressed through optimized braid architecture or surface modification methods [56,57]. The identified limitations highlight the need for mechanical optimization rather than merely maximizing elasticity, suggesting that viscoelasticity must be suitably aligned to facilitate effective wound closure.

13. CONCLUSION

Visco-elastically active silk sutures represent an innovative material for wound closure, addressing the limitations of conventional sutures in dynamic tissue environments. The integration of silk fibroin's inherent biocompatibility with engineered viscoelastic properties results in sutures that facilitate controlled stress relaxation, improved load distribution at wound margins, and enhanced conformity to the dynamics of living tissue. The significance of these traits is heightened in wounds located in regions of high motion, where conventional static sutures are prone to separation, resulting in unnatural scarring. Experimental data from in vitro studies, animal models, and preliminary clinical trials indicate that visco-elastic silk sutures enhance wound stability, promote organized collagen deposition, and reduce the incidence of hypertrophic or keloid scars relative to traditional silk or synthetic sutures. Additional functionalization techniques, such as bioactive and antimicrobial coatings, enhance therapeutic potential by reducing infection risk and modulating local inflammatory responses. Modified silk sutures are bioresorbable, offering advantages such as eliminating the need for removal and reducing patient discomfort. Despite these favorable attributes, challenges remain that must be addressed prior to their implementation in standard clinical practice. Factors encompass variations in viscoelastic performance under prolonged cyclic stress, the absence of standardized mechanical benchmarking relative to current suture materials, inadequate long-term clinical data in humans, and issues related to large-scale production, cost, and regulatory approval. The characteristics of surgical manipulation, knot integrity, and degradation patterns across various anatomical sites and patient demographics necessitate systematic evaluation. Visco-elastically active silk sutures provide a physiologically and mechanically informed method for dynamic wound management, potentially enhancing scar reduction and functional recovery. Future research should focus on standardized mechanical testing, well-structured comparative clinical studies, and scalable manufacturing methods to assess clinical significance and facilitate evidence-based integration into surgical practice.

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