Bioengineering Computer Models For Efficacy Research In Preventative And Treatment Wound Dressings

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Wound healing is a dynamic, multifactorial biological process influenced by various biomechanical, biochemical and environmental factors. Effective wound care relies heavily on dressings that are not only protective barriers but also active components in promoting tissue regeneration processes.

Modern dressings must be able to manage a variety of exudate types, maintain a moist wound healing environment, have antibacterial effect, regulate temperature, minimize trauma to the wound bed and peri-wound skin and deliver medications if needed. The design, optimization and evaluation of these complex devices have increasingly integrated bioengineering approaches, especially computational modeling and simulation approaches. Computational models provide a powerful, cost-effective alternative to traditional experimental trials by simulating dressing performance under real-world conditions which are known and controlled through the simulation protocols.[1]

In silico studies, using finite element analysis (FEA), computational fluid dynamics (CFD) and multiphysics simulations, offer key insights into how dressings interact with skin, wounds and surrounding tissues.[1-3] These models allow for the prediction of mechanical strain and stress distributions in soft tissues, temperature changes, exudate absorption, retention and spread and even drug release kinetics (see Figure 1).

For instance, swelling-induced tissue strains from superabsorbent dressings or the mechanical impact of adhesive removal on frail skin can be quantitatively evaluated through modeling and simulations.[3] Prevention-focused dressings are evaluated for their ability to alleviate soft tissue stress concentrations and reduce tissue shear exposures, while treatment dressings are studied for their fluid handling and drug delivery efficacy (if applicable).[1,4,5]

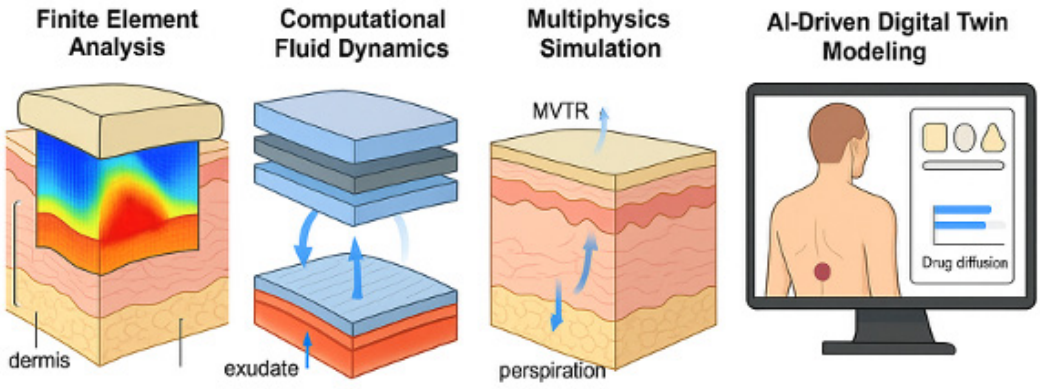

Figure 1: Potential applications of computational modeling in (left to right): (1) Modeling wound bed and peri-wound tissue stress states under dressings. (2) Modeling the exudate movement between and within the layers of a multilayer wound dressing and the dressing saturation patterns in order to avoid skin maceration. (3) Evaluating dressing performance in microclimate regulation and thermal management such as moisture-vapor transmission rate studies. (4) Artificial intelligence (AI)-powered modeling and simulations for personalized dressing selection and patient outcome predictions.

Artificial intelligence (AI) and machine learning (ML) are becoming integral to modeling simulation workflows.[6-8] These tools automate parameter optimization and facilitate predictive modeling based on vast datasets of clinical and biomechanical information. [6-8] The digital twin concept, creating a virtual patient-specific model, has opened the door to personalized dressing recommendations and real-time care simulations.[8] The growing role of computational modeling empowered by AI / ML in the development, evaluation and personalization of wound dressings, has direct implications for dressing research and development (R&D), as well as regulatory frameworks and pathways.[7] Specifically, these computational tools are especially valuable in the early stages of product development where multiple dressing formulations or configurations can be evaluated quickly and non-invasively.[7]

For instance, through modeling and simulation supported by experimental laboratory testing, researchers can predict how different dressing materials mechanically interact with each other and with skin, and also, how they influence the wound microclimate, balancing heat dissipation and moisture retention.[7,9,10] This eliminates the need for iterative physical prototypes and supports rapid innovation. Furthermore, computational modeling aids in understanding the biomechanical environment of the wound (for different wound etiologies), which is vital for preventing secondary complications like maceration, pressure ulcers / injuries and delayed healing. As these technologies become more accessible and integrated into industry workflows, their adoption is expected to expand beyond academic research institutions into standard industry R&D practice.

Computer Modeling And Simulations Of Dressing Performance

Computer models are now instrumental in understanding the functional behaviour of wound dressings across various clinical contexts. One of the earliest and most impactful applications is the use of finite element analysis (FEA) to study the mechanical protection offered by foam or multilayer dressings. For example, simulations show how silicone-foam dressings reduce peak strain energy densities at the sacrum or heel during prolonged bed rest.[1,2] If adequately constructed, prophylactic dressings are able to protect the skin and underlying tissues, preventing superficial and deep tissue injury by absorbing bodyweight or medical device-induced shear forces.[1] Adhesive dressing simulations use FEA to evaluate how dressing removal techniques influence skin deformations and strains.[3] In these models, computational representations of the skin

are subjected to peeling forces, revealing for example that soft silicone adhesives significantly reduce the risk of skin stripping compared to acrylic options.[3]

Computational fluid dynamics simulations can further aid in optimizing dressing design by simulating fluid movement within the porous structures of absorbent materials. This is essential for understanding how exudate is absorbed, retained, or evaporated. Such CFD modeling can predict for example dressing saturation points, capillary action across layers and moisture vapor transmission rates (MVTR), which are all critical for avoiding maceration and promoting healing. Diffusion models simulate drug-eluting dressings that deliver antibiotics, analgesics, growth factors or skin protector agents.[5] These models consider release rates, concentration gradients and tissue penetration depths, offering insights that guide dosage design without clinical trial repetition. A notable example includes the modeling of sodium pyruvate (NaPy) skin protectant release into sacral tissues, demonstrating clinically relevant delivery within hours.[5]

Multiphysics computational models go a step further by integrating FEA, CFD and heat transfer into one system. These simulations are used to study real-world scenarios, such as how perspiration impacts adhesion or how device-related heat buildup increases pressure ulcer risk. For instance, under continuous positive airway pressure (CPAP) masks, dressings with thermal conductivity closely matched to skin reduce local overheating, as confirmed by recently reported simulations and clinical observations.[9] Soon, AI-powered simulations will be able to predict dressing behaviour under varying patient conditions and adjust the dressing designs accordingly.[7]

Digital twin simulations allow clinicians to test dressing options on a virtual patient before applying them in practice, thereby minimizing trial-and-error. In the context of surgical wounds or diabetic foot ulcers, simulations can be used to model the interface between dressing materials and irregular tissue surfaces, thereby allowing clinicians to anticipate potential points of high pressure or shear that may impair healing.

Another key application is the simulation of fluid absorption in polymicrobial environments, where computational models can be used to predict how well a dressing can sequester harmful bacteria while maintaining optimal hydration. Such computational assessments inform both dressing selection and clinical protocols, particularly in high-risk populations. Additionally, these simulations can be adapted to represent specific clinical environments, such as intensive care units, operating rooms or long-term care settings, thereby increasing their translational relevance and optimizing their performance to the specific clinical context.

Regulatory And Clinical Translational Work

Computational modeling is gaining formal recognition as a scientifically valid component in the regulatory evaluation of medical devices in general, and wound dressings in particular.[11,12] The US Food and Drug Administration (FDA) and European regulatory bodies have issued guidance on the use of in silico trials and simulation data in medical device submissions. The *FDA Modernization Act 2.0* and similar frameworks explicitly support the use of virtual, computer modeling as a partial or full replacement for animal testing. This has major implications for wound dressing development, particularly in accelerating innovation cycles and reducing testing costs.

The Prophylactic Dressing Standards Initiative (PDSI), led by the author in collaboration with experts in this field, is currently developing international benchmarks for evaluating dressing efficacy using computational techniques.[13] Key metrics such as the protective efficacy index (PEI), the protective endurance (PEN) and the prophylactic trade-off design parameter (PTODP) provide standardized ways and quantitative metrics to assess how well a prophylactic dressing performs under bodyweight or medical device-generated forces, as well as environmental exposure such as presence of moisture.[1]

In clinical settings, computational modeling results are increasingly integrated into digital decision-support tools, where clinicians can simulate different dressings for a given patient based on their wound type, location and risk profile. For example, a digital twin of a sacral pressure ulcer / injury can predict how various dressings will interact with the wound, enabling the clinician to choose the most protective and least disruptive option.[2] Such modeling tools can also simulate long-term outcomes, such as time to saturation or risk of medical adhesive-related skin injuries (MARSIs), guiding dressing change intervals and removal protocols.[3] Importantly, these simulations must be validated through real-world data, including bench-top bioengineering and clinical studies.

Standardization of model assumptions, parameters, and output metrics is crucial to ensure reproducibility and regulatory acceptance.[13] Collaborations between bioengineers, clinicians and regulatory scientists are essential to bridge the gap between modeling predictions and bedside applications.[13] The integration of these models into real-world decision-making also supports economic efficiency. For example, by reducing the frequency of dressing changes or minimizing complications like MARSIs, hospitals can reduce costs and improve workflow efficiency. Computational modeling platforms are also beginning to support real-time simulations, which enable dynamic assessments of wound healing progress based on sensor data embedded in smart dressings.[7,14] These systems can alert clinicians to early signs of saturation or temperature shifts that may indicate infection or poor healing trajectories.

Regulatory agencies are now encouraging manufacturers to include validated computational modeling data in support of product claims, a trend that is likely to expand with further adoption of AI-driven technologies.

Conclusion

Computational modeling and simulations have already transformed the landscape of wound dressing research, development, manufacturing and application. These tools allow for precise assessment of biomechanical, biofluidic, biothermal, and biochemical dressing properties under realistic clinical conditions. From protecting fragile skin to optimizing drug release, in silico methods can now inform every stage of the dressing lifecycle, from design to regulatory approval to bedside use. The integration of AI and digital twins further supports real-time, patient-specific wound care planning, reducing risks and improving outcomes. With growing regulatory recognition and technological maturity, the future of wound care will be increasingly data-driven and personalized.

Moving forward, efforts should focus on expanding modeling capabilities to account for complex pathophysiological variables, enhancing cross-discipline collaborations and developing intuitive tools for clinical use.

As the wound care field continues to evolve and develop, computational bioengineering will remain a cornerstone of evidence-based, safe, clinically effective and cost-effective practice. Embracing advanced computational bioengineering as a foundational pillar in wound dressing development allows for unprecedented control over the quality of dressing products and the therapeutic environment. These technologies empower clinicians with actionable insights, researchers with rapid prototyping tools and regulatory bodies with standardized evidence of efficacy and safety. With multidisciplinary collaborations and continuous validation, computational modeling is positioned to lead the next phase of innovation in wound care, making precision, personalization and prevention through optimized products at sustainable prices the standard of care.

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