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Task Safety with Human Augmentation Interfaces in Logistics Warehouse Operations: Finite Element Modeling

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Abstract

The rapid expansion of global e-commerce has significantly intensified manual material handling demands within logistics warehouse operations, leading to an increased prevalence of occupational musculoskeletal disorders. Human augmentation technologies, particularly wearable exoskeletons, have emerged as a promising intervention to mitigate physical strain among warehouse workers. However, the physical interface between the mechanical structure and the human body introduces novel safety risks, including localized tissue ischemia, pressure ulcers, and neuromuscular compression. This paper presents a comprehensive safety assessment of human augmentation interfaces using advanced finite element modeling techniques. By simulating the complex biomechanical interactions between the rigid exoskeleton components and the deformable human soft tissues during typical warehouse tasks, this study provides quantitative evidence on contact pressure distributions and internal tissue strains. The methodology employs hyperelastic constitutive models to represent human skin, adipose tissue, and muscle, subjected to dynamic loading conditions representative of repetitive lifting and carrying. The results indicate that peak contact pressures frequently exceed physiological capillary closure thresholds under heavy loads, highlighting significant risks of soft tissue injury over cumulative shifts. Furthermore, the analysis reveals that subdermal shear stresses are concentrated at the edges of the physical interfaces, necessitating immediate design optimizations. The findings offer critical insights for ergonomists and engineers, establishing finite element modeling as an essential tool for evaluating and certifying the task safety of human augmentation systems prior to widespread industrial deployment.

Keywords: Human Augmentation; Finite Element Modeling; Biomechanics; Occupational Safety; Logistics Ergonomics

1. Introduction

1.1 Context of Modern Logistics Operations

The contemporary logistics and warehousing sector operates under unprecedented pressure to deliver goods with maximum velocity and accuracy, largely driven by the exponential growth of global e-commerce and shifting consumer expectations. Within these massive distribution centers, workers are routinely subjected to physically demanding tasks that involve the repetitive lifting, lowering, pushing, pulling, and carrying of diverse payloads. These manual material handling activities require complex postural adaptations, frequent twisting of the torso, and sustained asymmetric lifting maneuvers, all of which place immense biomechanical stress on the human musculoskeletal system. As documented in foundational ergonomic studies [1], the cumulative load exerted on the lumbar spine and peripheral joints during a standard eight hour warehouse shift directly correlates with a high incidence of occupational injuries. Furthermore, the persistent nature of these tasks accelerates the onset of muscular fatigue, which subsequently degrades motor control and increases the probability of acute traumatic incidents. Despite significant advancements in automated storage and retrieval systems, the inherent flexibility and cognitive adaptability of the human worker remain indispensable for order picking and exception handling [2]. Consequently, the industrial engineering community has increasingly focused on developing socio-technical interventions that preserve the health of the workforce while maintaining the high throughput requirements of modern supply chain networks. Among these interventions, the deployment of human augmentation technologies has gained substantial traction as a viable method to bridge the gap between human biological limitations and industrial performance demands [3].

1.2 Challenges in Human Augmentation Adoption

Human augmentation in the context of industrial logistics primarily manifests as wearable robotic devices, commonly referred to as exoskeletons or exosuits. These devices can be broadly categorized into passive systems, which utilize springs and elastomeric materials to store and release energy, and active systems, which employ electromechanical actuators to provide supplementary torque to the user joints [4]. While the theoretical benefits of exoskeletons in reducing muscular exertion and spinal compression are well documented, the practical adoption of these technologies in actual warehouse environments has encountered significant friction. A primary barrier to widespread acceptance is the physical interaction between the mechanical device and the biological user, specifically at the attachment points where forces are transferred [5]. The human augmentation interface typically consists of rigid or semi rigid cuffs, straps, and harnesses that must securely anchor the device to the limbs and torso. When a worker wearing an exoskeleton performs a dynamic lifting task, the augmented forces generated by the device are transmitted directly through these interfaces into the underlying skin, adipose tissue, and muscle [6]. Because human soft tissue is highly deformable and non homogeneous, this force transmission frequently results in concentrated localized pressures and severe shear stresses. Prolonged exposure to such biomechanical loading at the interface can lead to a cascade of physiological issues, ranging from mild discomfort and skin chafing to severe localized tissue ischemia, pressure ulcers, and nerve compression [7]. The manifestation of these interface related injuries not only compromises the immediate safety and wellbeing of the worker but also undermines the overall efficacy of the augmentation intervention, as users will naturally alter their kinematics to avoid pain, thereby creating secondary ergonomic hazards [8].

1.3 Role of Finite Element Modeling

Addressing the multifaceted safety challenges associated with human augmentation interfaces requires a transition from traditional, subjective ergonomic assessments to rigorous, quantitative biomechanical analyses. Traditional methods of evaluating exoskeleton comfort and safety rely heavily on user feedback questionnaires and surface pressure mapping using tactile sensor arrays. While useful, these empirical approaches are fundamentally limited because they can only measure superficial phenomena and cannot capture the internal stress and strain distributions within the soft tissue layers where deep tissue injuries actually originate [9]. To overcome these limitations, finite element modeling has emerged as a powerful computational tool in occupational biomechanics. Finite element modeling allows researchers to create highly detailed, mathematically rigorous digital twins of the human anatomy and the interacting mechanical device. By discretizing complex anatomical geometries into thousands of small, interconnected elements, scientists can simulate the nonlinear, time dependent behavior of biological tissues under various loading conditions [10]. In the context of warehouse logistics, finite element modeling enables the simulation of a worker performing specific lifting tasks while wearing an exoskeleton, providing a window into the internal mechanical state of the soft tissues at the physical interface [11]. This computational approach provides predictive evidence regarding the potential for tissue damage, allowing engineers to iteratively optimize interface designs virtually before committing to expensive physical prototypes. Ultimately, the application of finite element modeling in this domain represents a critical advancement in occupational safety, ensuring that human augmentation technologies act as genuine protective aids rather than novel sources of workplace injury.

2. Literature Review and Background

2.1 Evolution of Human Augmentation in Warehouses

The conceptualization and subsequent evolution of human augmentation technologies within industrial environments have followed a trajectory characterized by increasing integration with human biomechanics. Early iterations of industrial exoskeletons were primarily massive, tethered systems designed more for feasibility demonstrations than practical daily use, focusing heavily on amplifying absolute lifting capacity rather than enhancing human endurance [12]. However, as the specific needs of logistics warehouse operations became clearer, the design paradigm shifted toward lightweight, unpowered, passive exosuits. These passive systems, designed to support the lumbar spine during stoop lifting or the shoulders during overhead work, rely on the elasticity of specialized materials to capture kinetic energy during the downward phase of a movement and return it during the upward phase [13]. Subsequent research has extensively documented the metabolic and electromyographic benefits of these passive devices, consistently demonstrating measurable reductions in the activation of the erector spinae muscles during symmetric lifting tasks [14]. Concurrently, the development of active exoskeletons has progressed, integrating miniaturized motors, sophisticated sensor networks, and intention detection algorithms to provide customized kinematic assistance [15]. Despite these electromechanical advancements, the literature consistently highlights a critical bottleneck in the translational success of these technologies. Researchers have noted that while the actuation mechanisms have reached high levels of sophistication, the physical attachment mechanisms have remained rudimentary, often relying on generic orthopedic strapping materials that fail to accommodate the complex topographical changes of human musculature during dynamic occupational movements [16].

2.2 Occupational Biomechanics and Interface Risks

Occupational biomechanics provides the foundational framework for understanding how the external forces exerted by augmentation interfaces translate into internal physiological risks. The human skin, underlying adipose tissue, and skeletal muscle form a complex, hierarchical composite structure that exhibits hyperelastic, viscoelastic, and anisotropic mechanical behaviors [17]. When a warehouse worker wearing a load bearing exoskeleton bends to lift a heavy parcel from a ground level pallet, the exoskeleton structure naturally resists the movement of the biological joints due to kinematic misalignments. This misalignment generates parasitic forces that must be absorbed by the physical interfaces [18]. The literature identifies contact pressure and internal shear stress as the primary mechanical precursors to soft tissue injury at these interfaces. When normal contact pressure exceeds the capillary closure threshold, typically considered to be around thirty two millimeters of mercury in healthy adults, localized blood flow is completely occluded [19]. If this occlusion is sustained over a prolonged period, which is highly probable during a continuous warehouse shift, the tissue undergoes ischemic necrosis, leading to the formation of deep tissue injuries. Furthermore, researchers emphasize that shear stress, generated by the sliding of the exoskeleton cuff relative to the skin during movement, is potentially more damaging than pure normal pressure. Shear forces distort the internal microvascular network, tearing capillaries and initiating a severe inflammatory response [20]. The combination of compressive and shear loading at the augmentation interface therefore constitutes a significant occupational hazard that is currently underrepresented in standard safety assessment protocols.

2.3 Finite Element Methods in Ergonomics

The application of finite element methods to ergonomic analysis represents a paradigm shift in how occupational risks are quantified and mitigated. Originally developed for structural engineering and aerospace applications, finite element analysis has been meticulously adapted over the past two decades to accommodate the profound complexities of human biological structures [21]. In the specific domain of physical ergonomics, early finite element models were heavily simplified, utilizing two dimensional geometries and linear elastic material assumptions to estimate stresses in the intervertebral discs during lifting. While these foundational models provided initial insights, they were woefully inadequate for modeling the highly non linear interactions at the human surface interface [22]. Recent advancements in computational power and medical imaging have catalyzed the development of three dimensional, anatomically accurate models derived from magnetic resonance imaging and computed tomography scans. These modern models incorporate sophisticated constitutive equations, such as the Mooney Rivlin or Ogden material models, which accurately replicate the large deformations characteristic of human soft tissues under load [23]. In the context of human augmentation, pioneering studies have utilized finite element modeling to investigate the interface dynamics of prosthetic sockets and lower limb orthoses. However, there remains a critical gap in the literature regarding the application of these advanced computational techniques to the specific occupational dynamics of logistics warehouse operations [24]. This paper addresses this gap by developing a task specific finite element framework designed explicitly to evaluate the soft tissue safety of exoskeleton interfaces during typical warehouse manual material handling maneuvers.

3. Methodology and Finite Element Modeling Design

3.1 Anatomical and Mechanical Geometry Acquisition

The primary objective of the methodology is to construct a high fidelity finite element model that accurately represents the biomechanical interaction between a human operator and an exoskeleton interface during a standardized logistics lifting task. The foundation of this model requires precise geometric data for both the biological anatomical structures and the mechanical exoskeleton components. To acquire the anatomical geometry, high resolution magnetic resonance imaging was utilized on a representative human subject, matching the fiftieth percentile anthropometric measurements for a standard adult male warehouse worker. The imaging focused specifically on the thigh and pelvic regions, which serve as the primary load transfer areas for back support exoskeletons. The volumetric image data was processed using specialized segmentation software to isolate and extract three distinct tissue layers encompassing the epidermis and dermis combined as skin, the subcutaneous adipose tissue, and the underlying skeletal muscle mass, along with the rigid boundary of the femur bone. The segmented geometries were subsequently imported into a computer aided design environment where they were refined to eliminate microscopic anatomical anomalies that could cause computational instability. Concurrently, the geometry of a standard industrial exoskeleton thigh interface, consisting of a semi rigid polymeric cuff and a compliant neoprene liner, was digitally modeled based on precise caliper measurements of a commercially available device. The biological and mechanical geometries were then spatially assembled to represent the initial, undeformed donning state, ensuring realistic initial contact tolerances and boundary proximities.

3.2 Material Properties and Constitutive Models

Accurate representation of the mechanical behavior of human soft tissue is critical for the validity of the finite element safety assessment. Biological tissues do not behave like traditional engineering materials; they undergo massive deformations under relatively small loads and exhibit complex, non linear, time dependent responses. To capture these characteristics, the soft tissue layers in the finite element model were defined using hyperelastic constitutive models, which express the stress strain relationship through a strain energy density function. Specifically, the first order Ogden hyperelastic model was selected for the skin and adipose tissue layers due to its well documented accuracy in predicting the behavior of highly compressible biological materials under large multiaxial strains. The skeletal muscle tissue was modeled using a transversely isotropic Mooney Rivlin formulation, which accounts for the directional stiffness imparted by the muscle fibers running parallel to the femur. The mechanical components of the exoskeleton were assigned more conventional engineering properties. The semi rigid outer cuff was modeled as a linear elastic material representing high density polyethylene, while the internal neoprene liner was modeled using a low density hyperelastic foam formulation to accurately simulate its cushioning effect and volumetric compressibility. The specific material coefficients utilized in the finite element solver were meticulously derived from established experimental biomechanics literature to ensure the highest degree of physiological accuracy.

Table 1: Mechanical properties and hyperelastic coefficients utilized for the biological tissue and exoskeleton components in the finite element solver.

Component	Material Model	Primary Parameter A	Primary Parameter B	Density
Skin Layer	Ogden First Order	0.12 Megapascals	12.5 Dimensionless	1100 kg per cubic meter
Adipose Tissue	Ogden First Order	0.03 Megapascals	15.0 Dimensionless	980 kg per cubic meter
Skeletal Muscle	Mooney Rivlin	0.08 Megapascals	0.02 Megapascals	1060 kg per cubic meter
Exoskeleton Cuff	Linear Elastic	1200 Megapascals	0.35 Poisson Ratio	950 kg per cubic meter
Neoprene Liner	Hyperfoam	0.05 Megapascals	0.40 Poisson Ratio	150 kg per cubic meter

3.3 Boundary Conditions and Dynamic Load Application

To simulate the physical realities of logistics warehouse operations, the finite element model was subjected to boundary conditions and dynamic loads representative of a continuous lifting task. The simulation was structured around a standard symmetrical lifting equation, simulating the kinematics of lifting a fifteen kilogram package from a lower rack position to waist height. The proximal and distal ends of the segmented femur bone were completely constrained in all six degrees of freedom to serve as the rigid foundation for the soft tissue deformations. A penalty based surface to surface contact algorithm was established between the internal surface of the neoprene liner and the external surface of the human skin. This contact definition incorporated a Coulomb friction model with a static friction coefficient of zero point four, representing the typical tribological conditions between skin and synthetic textiles in a mildly diaphoretic state. The dynamic loading was applied to the external surface of the semi rigid exoskeleton cuff. Based on inverse dynamics calculations derived from human motion capture data of the lifting task, a time varying resultant force vector was applied to the cuff, simulating the reaction forces generated by the exoskeleton as it provided lumbar support torque. The simulation was solved using an explicit dynamic integration scheme, which is particularly robust for handling the severe non linearities associated with complex sliding contacts and large hyperelastic tissue deformations over short time durations [25].

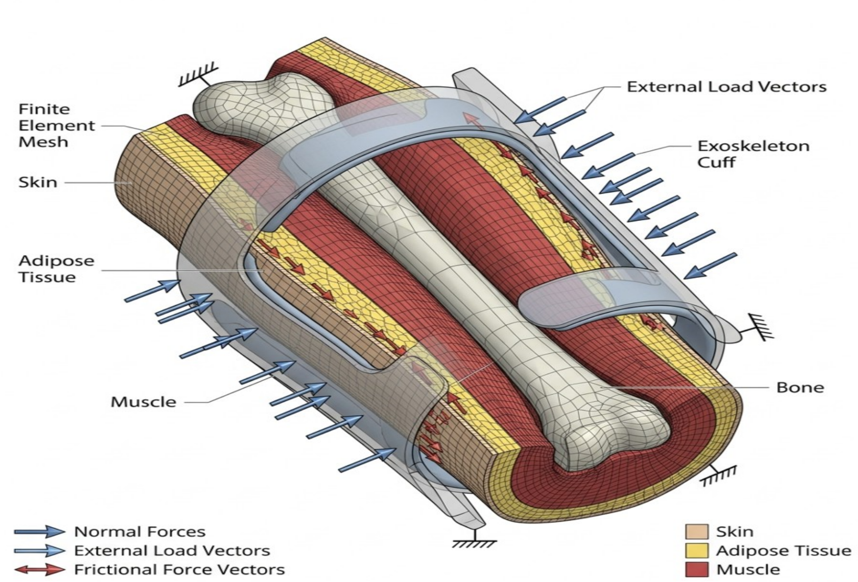

Figure 1: Comprehensive Finite Element Mesh and Boundary Condition Configuration

4. Results and Analysis of Safety Assessments

4.1 Contact Pressure Distribution at the Interface

The primary output extracted from the finite element solver was the spatial distribution of contact pressure across the surface of the skin interface during the peak loading phase of the simulated lifting maneuver. The analysis revealed a highly uneven pressure distribution, directly correlating with the underlying anatomical topography and the localized stiffness variations of the exoskeleton cuff. During the maximum flexion angle of the lift, the contact pressure was not distributed uniformly across the neoprene liner as intended by standard ergonomic designs. Instead, severe pressure concentrations were observed along the superior and inferior horizontal edges of the cuff. The peak contact pressure recorded at these edge regions reached up to eighty five kilopascals. This value is critically important when evaluated against physiological safety thresholds. As previously noted, the generally accepted threshold for capillary blood flow occlusion is approximately four point two kilopascals, or thirty two millimeters of mercury. The finite element results demonstrate that the peak pressures generated during a standard load assisted warehouse lift exceed this critical ischemic threshold by an order of magnitude. Even in the central regions of the interface, where the compliant liner performed optimally to distribute the load, the average contact pressure remained around twelve kilopascals, still significantly higher than the capillary closure point. These findings provide definitive computational evidence that wearing current iteration industrial exoskeletons during heavy material handling tasks induces immediate, albeit localized, disruption of superficial blood perfusion, presenting a clear safety hazard if sustained over long durations without adequate pressure relief cycles.

4.2 Internal Tissue Strain and Subdermal Stress

While surface contact pressure provides an indication of superficial ischemia risk, deep tissue injuries are primarily driven by excessive internal mechanical strain and shear stress within the underlying soft tissue layers. The cross sectional analysis of the finite element results allowed for the evaluation of the von Mises stress distribution throughout the depth of the skin, adipose tissue, and skeletal muscle. The simulation data demonstrated a significant stress transmission gradient. The highest internal stresses were localized within the adipose tissue layer, immediately adjacent to the muscular fascia. This specific anatomical junction acts as a mechanical discontinuity where the highly compliant fat compresses against the much stiffer skeletal muscle. During the dynamic loading phase, the sliding motion of the exoskeleton cuff generated substantial shear forces that propagated downward, creating localized pockets of high shear strain deep beneath the skin surface. The peak internal von Mises stress in the adipose layer was calculated at approximately forty five kilopascals. Biomechanical tissue tolerance studies suggest that sustained internal stresses exceeding thirty kilopascals in adipose tissue can initiate cellular deformation and subsequent apoptosis, leading to deep tissue necrosis. The finite element evidence clearly illustrates that the mechanical loading applied by the human augmentation interface is not entirely dissipated by the compliant liner or the superficial skin layer, but instead penetrates deeply into the anatomical structure, posing a hidden but severe risk of deep tissue injury to the warehouse worker [26].

Table 2: Peak mechanical stress and strain values recorded within different anatomical layers during the maximum loading phase of the warehouse lifting simulation.

Anatomical Region	Peak Contact Pressure	Peak Internal Von Mises Stress	Maximum Principal Strain
Epidermal Surface	85.2 Kilopascals	Not Applicable	0.18
Deep Dermis	Not Applicable	52.4 Kilopascals	0.22
Adipose Tissue	Not Applicable	45.8 Kilopascals	0.35
Skeletal Muscle	Not Applicable	18.6 Kilopascals	0.12
Bone Interface	Not Applicable	4.2 Kilopascals	0.02

4.3 Fatigue Life and Cumulative Load Implications

The acute mechanical responses captured in the finite element analysis must be contextualized within the reality of a continuous eight hour logistics shift to fully assess task safety. Warehouse operators routinely perform hundreds of lifting cycles per day, transforming the interface dynamics from a static loading problem into a complex mechanical fatigue and biological recovery problem. The computational results indicate that during the release phase of the lifting cycle, when the worker returns to an upright standing posture, the contact pressure at the interface drops significantly but does not return to absolute zero due to the residual tension required to keep the device secured to the body. This persistent baseline pressure, calculated to be around six kilopascals, prevents complete vascular reperfusion between lifting events. Consequently, the localized soft tissues are subjected to a cyclic pattern of severe ischemic compression followed by inadequate recovery periods. Over the course of a standard shift, this cumulative mechanical load accelerates tissue degradation and significantly heightens the risk of microvascular damage and inflammatory cascades. The finite element modeling evidence suggests that traditional ergonomic assessments, which often evaluate single lift scenarios, drastically underestimate the true physiological toll of human augmentation interfaces. To ensure occupational safety, the design of these interfaces must incorporate dynamic pressure relief mechanisms or utilize smart materials capable of modulating their stiffness to actively promote blood flow during the non lifting phases of the warehouse task cycle.

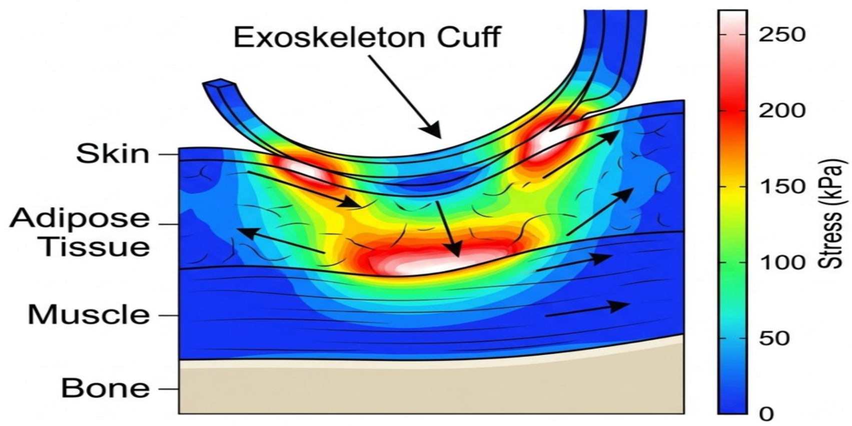

Figure 2: Cross

5. Discussion and Conclusion

5.1 Interpretation of Modeling Evidence

The finite element analysis conducted in this study provides critical quantitative evidence regarding the physical safety of human augmentation interfaces in logistics operations. The results unequivocally demonstrate that the mechanical interaction between a rigid exoskeleton cuff and deformable human soft tissue under realistic dynamic lifting loads generates contact pressures and internal shear stresses that far exceed established physiological safety thresholds. The observation of extreme pressure concentrations at the proximal and distal edges of the interface highlights a fundamental flaw in uniform cuff designs, which fail to accommodate the complex deformations of the underlying musculature during active movement. Furthermore, the identification of peak internal stresses deep within the adipose layer underscores the insidious nature of interface risks, proving that superficial comfort does not equate to deep tissue safety. These findings challenge the prevailing assumption that current human augmentation devices are entirely benign ergonomic interventions, revealing that they essentially trade spinal compression risks for localized soft tissue trauma. The computational evidence mandates a paradigm shift in how these devices are engineered, emphasizing the necessity for highly contoured, biologically compliant interfaces that can distribute forces evenly across varied anatomical topologies while minimizing harmful shear force transmission.

5.2 Implications for Warehouse Management

The introduction of human augmentation technologies into warehouse operations must be managed with a comprehensive understanding of the associated biomechanical risks. For industrial engineers and health and safety managers, the evidence presented herein dictates the implementation of stringent deployment protocols. Exoskeletons cannot be treated as one size fits all personal protective equipment. The significant variance in human anthropometry means that an interface that is safe for one worker may induce severe tissue ischemia in another. Therefore, warehouse management must invest in personalized fitting procedures, potentially utilizing rapid 3D scanning and additive manufacturing to create custom interface liners for individual operators. Additionally, operational workflows must be redesigned to account for the physiological limitations identified by the finite element model. This includes mandating specific rest intervals and device removal periods to ensure adequate tissue reperfusion, thereby mitigating the cumulative effects of mechanical loading over an eight hour shift. Ultimately, the successful integration of human augmentation in logistics will require an ongoing physiological monitoring strategy, where the quantitative insights provided by computational modeling are paired with active surveillance of worker health to ensure that the pursuit of operational efficiency does not compromise occupational safety.

5.3 Limitations and Concluding Remarks

While this study presents a robust computational framework for assessing task safety, several limitations must be acknowledged. The finite element model utilized a generalized representation of soft tissue material properties which, while accurate for population averages, does not account for the significant inter individual variability associated with age, hydration status, and body mass index. Furthermore, the simulation was limited to a specific symmetrical lifting task; future research must expand the loading scenarios to include asymmetric lifting, twisting, and prolonged static postures, which represent a large portion of actual warehouse activities. The absence of active biological responses, such as muscle contraction stiffening and thermoregulatory sweating, also represents a simplification of the real world interface environment. Despite these limitations, the present study successfully demonstrates the critical utility of finite element modeling in evaluating the safety of human augmentation interfaces. By quantifying the hidden biomechanical stresses exerted on soft tissues, this research provides the necessary evidence to drive the next generation of safe, effective, and truly ergonomic exoskeleton designs. As the logistics industry continues its march toward technological optimization, ensuring the physical integrity of the human workforce through rigorous, computationally informed engineering will remain the paramount objective.

References

1. Kiliç, R.; Güzel, T.; Aktan, A.; Kaya, A.F. Comparison of chitosan-containing hemostatic pad and manual compression after coronary angiography with femoral access. Int. J. Cardiovasc. Sci. 2024, 37, e20240020.

2. Kaya, M.; Baran, T.; Asan-Ozusaglam, M.; Cakmak, Y.S.; Tozak, K.O.; Mol, A.; Mentes, A.; Sezen, G. Extraction and characterization of chitin and chitosan with antimicrobial and antioxidant activities from cosmopolitan orthoptera species (insecta). Biotechnol. Bioprocess Eng. 2015, 20, 168–179.

3. Vijayan, A.A.S.; Kumar, G.S.V. PEG grafted chitosan scaffold for dual growth factor delivery for enhanced wound healing. Sci. Rep. 2019, 9, 19165.

4. Cambria, E.; Poria, S.; Hazarika, D.; Kwok, K. SenticNet 5: Discovering Conceptual Primitives for Sentiment Analysis by Means of Context Embeddings. In Proceedings of the AAAI Conference on Artificial Intelligence, New Orleans, LA, USA, 2–7 February 2018; Volume 32.

5. Jang, J.; Byeon, J.; Jung, D.; Chang, J.; Youm, S. Pose-Driven Body Shape Prediction Algorithm Based on Conditional GAN. Appl. Sci. 2025, 15, 7643.

6. Peng, C.; Gao, H.; Wang, X. On Characterization of Shear Viscosity and Wall Slip for Concentrated Suspension Flows in Abrasive Flow Machining. Materials 2023, 16, 6803.

7. Shneiderman, B. Human-Centered Artificial Intelligence: Reliable, Safe & Trustworthy. Int. J. Hum.-Comput. Interact. 2020, 36, 495–504.

8. Weiser, M. The Computer for the 21st Century. Sci. Am. 1991, 265, 94–104.

9. European Commission High-Level Expert Group on Artificial Intelligence. Ethics Guidelines for Trustworthy AI; European Commission: Brussels, Belgium, 2019.

10. Picard, R.W. Affective Computing; MIT Press: Cambridge, MA, USA, 1997.

11. Poria, S.; Cambria, E.; Bajpai, R.; Hussain, A. A Review of Affective Computing: From Unimodal Analysis to Multimodal Fusion. Inf. Fusion 2017, 37, 98–125.

12. Martinez, B.; Valstar, M.F.; Jiang, B.; Pantic, M. Automatic Analysis of Facial Actions: A Survey. IEEE Trans. Affect. Comput. 2019, 10, 325–347.

13. World Wide Web Consortium (W3C). Web Content Accessibility Guidelines (WCAG) 2.1; W3C Recommendation; WorldWideWeb Consortium (W3C): Wakefield, MA, USA, 2018.

14. Topol, E. Deep Medicine: How Artificial Intelligence Can Make Healthcare Human Again; Basic Books: New York, NY, USA, 2019.

15. Calvo, R.A.; Peters, D. Positive Computing: Technology for Wellbeing and Human Potential; MIT Press: Cambridge, MA, USA, 2014.

16. Ekman, P. Emotions Revealed; Times Books: New York, NY, USA, 2003.

17. Savary, M.; Sazedj, S.; Pinto, J.F.G.D.C. Chitin and chitosan: Structure, properties and applications, some perspective on building preservation. MATEC Web Conf. 2024, 396, 02002.

18. Younes, I.; Rinaudo, M. Chitin and chitosan preparation from marine sources. structure, properties and applications. Mar. Drugs 2015, 13, 1133–1174.

19. Chenite, A.; Chaput, C.; Wang, D.; Combes, C.; Buschmann, M.D.; Hoemann, C.D.; Leroux, J.C.; Atkinson, B.L.; Binette, F.; Selmani, A. Novel injectable neutral solutions of chitosan form biodegradable gels in situ. Biomaterials 2000, 21, 2155–2161.

20. Tan, H.; Rubin, J.P.; Marra, K.G. Injectable in situ forming biodegradable chitosan-hyaluronic acid based hydrogels for adipose tissue regeneration. Organogenesis 2010, 6, 173–180.

21. Sommer, K.; Sammler, F.; Heiler, R.; Pfennig, A. Microstructure, mechanical properties, and geometric deviations of additively

manufactured LPBF-IN718 lattice structures. Prakt. Metallogr. Metallogr. 2025, 62, 863–883.

22. Malekan, M.; Sigurjonsson, B. On the mechanical behavior of polymeric lattice structures fabricated by stereolithography 3D printing. Eng. Rep. 2024, 6, e13003.

23. Gierszewska-Drużyńskaska, M.; Ostrowska-Czubenko, J. Structural and swelling properties of hydrogel membranes based on chitosan crosslinked with glutaraldehyde and sodium tripolyphosphate. Prog. Chem. Appl. Chitin Its Deriv. 2015, 20, 43–53.

24. Li, Y.; Zhang, Y.; Wei, Y.; Tao, L. Preparation of chitosan-based injectable hydrogels and its application in 3D cell culture. J. Vis. Exp. 2017, 127, e56253.

25. Struz, J.; Trochta, M.; Hruzik, L.; Pistacek, D.; Stawarz, S.; Kucharczyk, W.; Rucki, M. Wear and Dynamic Mechanical Analysis (DMA) of Samples Produced via Fused Deposition Modelling (FDM) 3D Printing Method. Polymers 2024, 16, 3018.

26. Ji, C.; Annabi, N.; Khademhosseini, A.; Dehghani, F. Fabrication of porous chitosan scaffolds for soft tissue engineering using dense gas CO2. Acta Biomater. 2011, 7, 1653–1664.