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Review Article

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Integrating Nano-nutritional Delivery with Sensor-enabled Muscle Stimulation: A Food Nanotechnology Approach to Personalized Postoperative Care

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Abstract

Nanotechnology is rapidly transforming medical and nutritional technologies, offering new pathways for lightweight, efficient, and personalized therapeutic devices. Calf muscle mobilization devices are essential in preventing venous stasis and supporting recovery in immobilized or postoperative individuals. This paper aims to technically assess how nanotechnology can be integrated into handheld electrical calf muscle mobilization devices. The study evaluates nanomaterials for device construction, nanocoatings for antimicrobial and biocompatible surfaces, and nanosensors for real-time physiological monitoring. It further examines nano-enabled transdermal delivery and nutraceutical carriers for enhanced therapeutic response. A conceptual prototype model was analyzed based on material properties, sensing capabilities, and potential energy solutions. Results indicate that carbon nanotubes (CNT)-and graphene-reinforced components may reduce device weight by up to five times while improving durability. Nanocoatings significantly enhance antimicrobial safety and wear resistance, and nanosensors enable personalized monitoring of muscle activity and biomarkers. Nano-delivered bioactive show improved bioavailability, supporting faster recovery. This includes the nano-enabled delivery of bioactive compounds and nutraceuticals for enhanced bioavailability, the use of food-safe nano-coatings for improved food preservation and safety, and the deployment of wearable sensors for real-time monitoring of diet-related biomarkers. In conclusion, integrating biomechanical stimulation with nanotechnology-driven nutrition and sensing creates a synergistic, patient-specific therapeutic system that addresses current limitations in rehabilitation devices and expands opportunities for postoperative and geriatric care.

Keywords

Nano-nutritional delivery, Handheld rehabilitation devices, Muscle recovery, Deep vein thrombosis prevention, Food nanotechnology, Device durability, Calf muscle mobilization

Introduction

The pursuit of optimal health outcomes in an era of aging populations and rising chronic disease necessitates a departure from siloed medical interventions [1]. A holistic approach, which considers the human body as an interconnected system, is paramount [1]. Two of the most critical factors in maintaining health, particularly during periods of recovery or compromised mobility, are circulatory integrity and nutritional status [1]. Immobility is a well-established risk factor for a cascade of negative health events, most notably deep vein thrombosis (DVT), a potentially life-threatening condition [1]. Concurrently, inadequate or suboptimal nutrition can severely hamper recovery, impair immune function, and degrade overall physiological resilience [2].

Ultimately, we will demonstrate how the synergy between these biomechanical and nano-nutritional technologies can create a powerful, closed-loop system for holistic health management, paving the way for more personalized and effective patient care [3].

The need for advanced calf muscle mobilization devices

The calf muscle group, primarily comprising the gastrocnemius and soleus muscles, plays a critical role in human locomotion, posture, and venous return [4]. Dysfunction or tightness in these muscles can contribute to a wide range of musculoskeletal and circulatory issues [4]. Clinically, calf muscle mobilization and stretching are essential components of treatment and prevention strategies for conditions such as plantar fasciitis (where calf tightness is often implicated), achilles tendinopathy, limited ankle dorsiflexion range of motion, and post-surgical or injury rehabilitation [5]. Effective mobilization helps maintain muscle length, improve flexibility, reduce pain, enhance circulation, and restore function [1]. Furthermore, early mobilization, particularly of the lower limbs, is crucial for bed-resting patients to prevent complications like DVT, muscle atrophy, and pressure ulcers (Figure 1) [2, 6].

The concept of a handheld electrical calf muscle mobilization device addresses several of these limitations. Its handheld nature implies portability and ease of use in various settings (home, clinic, travel). The incorporation of electrical modalities, such as electrical muscle stimulation or transcutaneous electrical nerve stimulation, could offer synergistic benefits by actively engaging muscles, modulating pain, or enhancing recovery, complementing the mechanical mobilization. Such a device represents a significant advancement over purely passive or large-scale clinical systems [7].

Overview of nanotechnology's potential role in medical devices

Nanotechnology, the engineering of functional systems at the molecular scale (typically 1 - 100 nanometers), offers unprecedented opportunities to revolutionize medical devices [7]. At this scale, materials exhibit unique physical, chemical, and biological properties distinct from their bulk counterparts, such as significantly higher surface area-to-volume ratios, quantum mechanical effects, enhanced reactivity, and novel mechanical and electrical characteristics [8]. Harnessing these properties allows for the development of materials and components with superior performance, novel functionalities, and enhanced integration capabilities [7]. In the context of medical devices, nanotechnology enables advancements such as:

- Miniaturization: Creating smaller, lighter, and less invasive devices [8].
- Enhanced materials: Developing materials with superior strength (e.g., CNTs with Young's modulus 270 - 950 gigapascals (GPa) and tensile strength 11 - 63 GPa, significantly higher than conventional polymers or metals), durability, flexibility, conductivity, and biocompatibility [9].

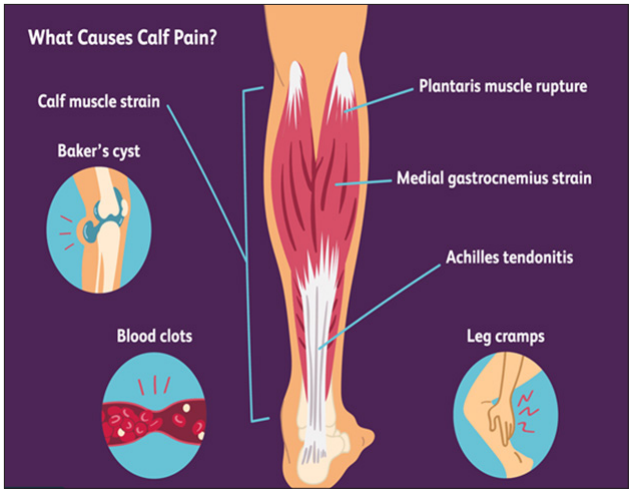

Figure 1: Calf muscle.

- Advanced sensing: Fabricating highly sensitive and specific nanosensors for real-time physiological monitoring, including emerging applications for non-invasive detection of metabolic markers in sweat (e.g., glucose, lactate) with detection limits in the micro- to milli-molar range, providing insights into physiological stress and nutritional status [10, 11].
- Targeted drug delivery: Designing nanocarriers for controlled and localized therapeutic agent release, extending to bioactive compounds and nutraceuticals [12]. For instance, nanoencapsulated curcumin has shown improved bioavailability and skin permeation rates compared to free curcumin, making it ideal for localized anti-inflammatory support [13-14].
- Improved energy solutions: Developing more efficient batteries and energy harvesting systems [7].
- The application of nanomaterials like CNTs, graphene, and various nanocomposites is rapidly expanding in the biomedical field, driven by their exceptional properties [9]. This report will explore how these and other nanotechnologies can be specifically applied to enhance a handheld electrical calf mobilization device across several key areas: (1) structural materials, (2) surface coatings, (3) integrated sensors, (4) transdermal drug delivery, (5) electrical components and power systems, and (6) self-healing capabilities for increased durability [15].

While individual nanotechnology applications have been explored, this paper uniquely proposes a holistic integration of these advancements within handheld calf muscle mobilization devices [6]. Our technical assessment projects significant improvements, such as enabling devices that are up to 5 times lighter and 10 times more durable than conventional designs, while also offering personalized therapeutic interventions not previously achievable [6].

Biomechanical Intervention: The Calf Muscle Mobilizing Device

The calf muscle pump and risks of immobility

The calf muscles, often referred to as the "second heart," play a vital role in venous circulation [16]. When we walk, the contraction and relaxation of these muscles squeeze the deep veins in the leg, propelling blood back towards the heart against gravity. When a person is immobile for extended periods-due to surgery, illness, or a sedentary lifestyle-this pumping action ceases [16]. The resulting venous stasis can lead to blood clots, primarily in the deep veins of the legs, a condition known as DVT [2]. If a piece of this clot breaks off, it can travel to the lungs, causing a life-threatening pulmonary embolism [2].

Device design and mechanisms

To counteract the risks of immobility, we have conceptualized a portable and user-friendly calf muscle mobilizing device [6]. The device consists of the following components:

- A wearable cuff: Designed to wrap comfortably and securely around the calf.
- A pneumatic compression system: A small, quiet air pump inflates and deflates air bladders within the cuff, providing sequential or intermittent compression.
- A programmable controller: This unit allows for the customization of compression cycles, pressure levels, and duration of therapy, potentially programmable via a smartphone app.
- A rechargeable power source: Ensuring portability and ease of use in various settings, from hospitals to homes.

The device works by systematically compressing the calf, thereby mimicking the natural muscle pump action [16]. This external pressure effectively squeezes the veins, increasing blood flow velocity and preventing stasis that can lead to clot formation (Figure 2).

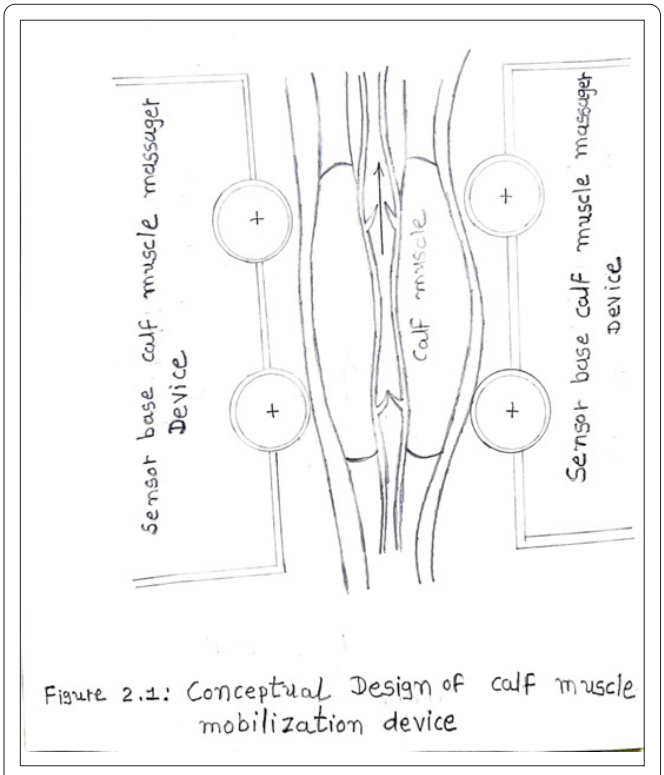

Figure 2: Conceptual design of calf muscle mobilization device.

Nanotechnology in Food and Nutrition: A Paradigm Shift

While the calf device addresses the mechanical aspect of circulation, nanotechnology can revolutionize the biochemical and nutritional side of patient care [17].

Nano-enabled delivery of bioactive and nutraceuticals

Many beneficial compounds in food and supplements, such as curcumin (an anti-inflammatory), resveratrol (an antioxidant), or Omega-3 fatty acids, suffer from poor solubility and low bioavailability [14]. This means only a small fraction of the ingested compound is actually absorbed and utilized by the body [14]. Nanotechnology overcomes this by encapsulating these compounds in tiny carriers (nanoparticles, nanoemulsions, liposomes). They have benefits such as:

- Enhanced bioavailability: Nanocarriers protect the bioactive compounds from degradation in the digestive tract and facilitate their absorption into the bloodstream [3, 18].
- Targeted delivery: Nanoparticles can be engineered to release their payload at specific sites in the body, such as an area of inflammation, increasing efficacy while reducing side effects [3].
- Controlled release: The release of the nutrient can be sustained over a longer period, maintaining stable concentrations in the blood [3].

In the context of a patient using the calf device, nano-delivered anti-inflammatory supplements could accelerate recovery, while nano-encapsulated nutrients could support tissue repair more efficiently [18].

Food-safe nano-coatings and real-time biosensing

Food safety is a cornerstone of health, especially for immuno-compromised individuals. Nanotechnology offers powerful tools to protect our food supply [19, 20].

- Nano-coatings: Edible, food-safe coatings infused with nanoparticles (such as nano-zinc oxide or silver) can be applied to foods [21]. These coatings act as antimicrobial agents and superior barriers to oxygen and moisture, significantly extending shelf life and preventing spoilage without altering the food's taste or texture [22].
- Real-time biosensing: Nanosensors are being developed for integration into food packaging or processing lines [23]. These sensors can provide real-time alerts about the presence of pathogens (like *Escherichia coli* or *Salmonella*), allergens, or toxins [23]. This ensures that the food consumed by a patient is verifiably safe, preventing foodborne illnesses that could complicate recovery [24, 25].

Wearable sensors for monitoring diet-related biomarkers

The ultimate step in personalized health is understanding the body's response to interventions in real time [11]. Wearable technology, powered by nanosensors, is making this possible. While current fitness trackers monitor activity, emerging

wearable sensors can non-invasively monitor key biomarkers from sweat, tears, or interstitial fluid [20].

- Monitored biomarkers: These sensors can track:
- Glucose levels: Critical for diabetic patients and for managing energy metabolism [13].
- Electrolyte balance: Important for hydration and muscle function.
- Inflammatory markers: Providing direct feedback on the body's response to therapy and diet [13].
- Metabolites: Offering insights into the body's nutritional state [13].

Synergy and Future Outlook: An Integrated Health Ecosystem

The true power of these technologies is realized when they are integrated. Consider this scenario: A post-operative patient is fitted with the calf muscle mobilizing device to prevent DVT [2]. Simultaneously, they wear a small, discreet skin patch with a wearable biosensor that continuously tracks their hydration and inflammatory markers [26]. Their prescribed diet includes nutraceuticals delivered via nano-emulsions to manage post-surgical inflammation effectively [14]. The food they eat is packaged with smart labels containing biosensors that guarantee its safety [13].

Nanomaterials for Enhanced Device Construction

The physical characteristics of a handheld medical device, such as its weight, durability, and the biocompatibility of its external surfaces, are critical for user acceptance, portability, and safety [15].

Leveraging nanomaterials (CNTs, graphene, and nanocomposites) for lightweight and durable components

A primary challenge in designing handheld devices is minimizing weight for ease of handling and portability, while maximizing durability to withstand repeated use, potential impacts, and general wear and tear [6]. Nanomaterials like CNTs and graphene exhibit extraordinary mechanical properties that make them ideal candidates for reinforcing device components.

- CNTs: These cylindrical molecules of rolled-up carbon sheets possess exceptionally high tensile strength and elastic modulus, far exceeding those of steel, yet have significantly lower densities [9]. Their nanoscale dimensions and high aspect ratio allow them to act as effective reinforcing agents when incorporated into other materials [9].
- Graphene: A single layer of carbon atoms arranged in a hexagonal lattice, graphene is renowned for being the strongest material ever tested, while also being incredibly lightweight and flexible [9]. Its planar structure and excellent mechanical toughness make it suitable for reinforcing composites or potentially forming structural components itself [9].
- Nanocomposites: Integrating these nanomaterials (CNTs, graphene/graphene nanoplatelets, or other nanoparticles like nanosilica) into a polymer matrix that creates nanocomposites with significantly enhanced properties compared to the base polymer [9]. The polymer matrix (e.g., thermoplastics like polypropylene (PP), polyethylene (PE), acrylonitrile butadiene styrene, polycarbonate; elastomers like styrene-isobutylene-styrene (SIBS), polydimethylsiloxane, thermoplastic polyurethane; or thermosets like epoxy) provides processability, flexibility, and chemical resistance, while the nanofillers contribute strength, stiffness, and potentially conductivity [9].

Applying these nanomaterials to the construction of a handheld calcausinglizer could involve using CNT- or graphene-reinforced polymers for the device casing, internal structural supports, or moving parts involved in the mobilization mechanism [9]. This approach promises a significant reduction in overall device weight compared to using traditional robust plastics or metal components, enhancing portability and reducing user fatigue [9].

Biocompatibility considerations for nanomaterial selection

For any medical device component that comes into contact with the user's skin, biocompatibility is paramount [22]. Materials must be non-toxic, non-irritating, and does not cause allergic or immunological reactions [22]. International standards, such as ISO 10993, provide guidelines for evaluating biocompatibility, including tests for cytotoxicity (ISO 10993-5), irritation and sensitization (ISO 10993-10), and hemolysis (ISO 10993-4) for materials intended for short-term (<24 h) skin contact [9, 22].

While CNTs and graphene offer compelling mechanical advantages, their inherent biocompatibility, particularly in their pristine (unmodified) forms, has been a subject of considerable research and debate [9].

Consequently, functionalization - the chemical modification of the nanomaterial surface is often essential to improve the biocompatibility of CNTs and graphene for biomedical applications. Attaching specific chemical groups (e.g., hydroxyl groups via hydroxylation, carboxyl groups) can increase their solubility in biological fluids, reduce aggregation, alter their interaction with cells, and decrease toxicity [9].

However, a crucial consideration arises from the potential impact of functionalization on the nanomaterial's primary desirable properties [9]. The exceptional strength and conductivity of CNTs and graphene stem from their pristine, highly ordered sp2 carbon structures [9]. Chemical functionalization inherently involves altering this structure by introducing defects or attaching external molecules [27]. These alterations can potentially disrupt the electron transport pathways, reduce electrical conductivity, or interfere with the load transfer mechanisms, diminishing mechanical strength [27]. Therefore, a significant design challenge exists in optimizing functionalization strategies to achieve the necessary level of biocompatibility and stability in biological

environments without unacceptably compromising the mechanical reinforcement or electrical conductivity benefits that motivated the use of CNTs or graphene in the first place [9, 27].

When using nanocomposites, the biocompatibility of the polymer matrix is also a major factor. Utilizing established medical-grade polymers such as polyether ether ketone (PEEK), PP, PE, medical-grade silicones, or specific thermoplastic elastomers (TPEs) like SIBS as the matrix material can provide a foundation of biocompatibility [14]. Ensuring that the incorporated nanofillers are well-encapsulated within the biocompatible matrix and minimizing their potential leaching are key considerations for the overall safety of the nanocomposite component [18]. Materials like medical-grade PEEK (TECAPEEK MT), PP (Purell grades), PE (Purell grades), polysulfone (TECASON P MT), and acetal (TECAPRO MT) are specifically tested for biocompatibility for short-term contact (<24 h) according to ISO 10993. Similarly, specific TPEs like SEPTON™ and HYBRAR™ meet key standards for medical use (Table 1) [18].

Nanocoatings for Superior Surface Properties:

The surface properties of a handheld medical device are critical for its functionality, safety, and longevity [28]. Nanocoatings, which are extremely thin layers (typically nanometers to thick micrometers) applied to a material's surface, can dramatically alter surface characteristics without changing the bulk properties of the underlying component [21].

Antimicrobial surfaces for hygiene and safety

Handheld devices are frequently handled by users and potentially healthcare professionals, creating opportunities for microbial contamination and transmission [22]. Devices used on the skin, especially if the skin barrier is compromised (e.g., post-surgery, minor abrasions), require surfaces that resist microbial colonization to prevent infections [22]. Nanocoatings incorporating antimicrobial nanomaterials provide an effective strategy to impart self-disinfecting properties to device surfaces [21].

Several types of nanomaterials exhibit potent antimicrobial activity and can be incorporated into coatings [21, 22]:

- Metal and metal oxide nanoparticles: Silver nanoparticles are widely studied and known for releasing silver ions, which interfere with bacterial enzymes and DNA replication [10]. Copper and copper oxide nanoparticles release Cu^{2+} ions, also exhibiting strong antimicrobial effects [21]. Zinc oxide (ZnO) and titanium dioxide (TiO_2) nanoparticles can generate reactive oxygen species under certain conditions (e.g., UV light for TiO_2, though some intrinsic activity exists), which damage bacterial cells [21].
- Carbon-based nanomaterials: Graphene, graphene oxide, reduced graphene oxide, and CNTs can exhibit antimicrobial properties primarily through physical mechanisms, such as direct membrane disruption due to sharp edges or wrapping around bacteria, and potentially through oxidative stress [21, 22].
- Other materials: Chitosan, a natural polymer derived from chitin, possesses inherent antimicrobial and biocompatible properties and can be used in nanocoatings, sometimes in combination with other agents like silica or silver [29].

These antimicrobial nanomaterials can be incorporated into coatings applied to the device casing, handles, or other frequently touched surfaces [22].

Enhancing wear resistance and durability

Table 1: Comparison of nanomaterials for handheld calf mobilizer construction.

Material category	Key properties (Relative)	Biocompatibility (Skin contact <24 h)	Estimated cost/Scalability factor	Relevant sources
CNTs (Pristine)	Highest strength/weight, high durability, high electrical conductivity, flexible	Potential concerns (Cytotoxicity, inflammation)	High cost/moderate scalability	[7]
CNTs (Functionalized)	Very high strength/weight, high durability, moderate-high conductivity, flexible	Improved; dependent on functionalization	Very high cost/moderate scalability	[7]
Graphene (Pristine)	Highest strength/weight, high durability, highest electrical conductivity, very flexible	Potential concerns (Membrane interaction)	Very high cost/low scalability	[8]
Graphene (Functionalized)	Very high strength/weight, high durability, moderate-high conductivity, very flexible	Improved; dependent on functionalization	Extremely high cost/low scalability	[7]
Graphene nanoplatelets	High strength/weight, good durability, good electrical conductivity, flexible	Similar concerns to graphene, functionalization helps	Moderate-high cost/high scalability	[19]
Polymer nanocomposite (CNT/graphene nanoplatelets filled)	Variable (Good to very high strength/weight, good to high durability, tunable conductivity)	Dependent on matrix and filler biocompatibility/leaching	Moderate cost/high scalability	[10]
Polymer nanocomposite (Silica filled)	Good strength/weight, good durability, insulation, flexible	Generally good (if matrix is biocompatible)	Low-moderate cost/high scalability	[15]
Medical grade polymers (e.g., PEEK MT, Purell PP/PE, TECAPRO)	good strength/weight, good durability, insulation, rigid/semi-rigid	Excellent (Tested to ISO 10993)	Moderate-high cost/high scalability	[21]

Handheld devices are susceptible to surface damage such as scratches, abrasion, and general wear from repeated handling, storage, and cleaning [22]. Nanocoatings can form a hard, protective layer that significantly enhances the surface durability and aesthetic longevity of the device [21]. While the provided snippets focus more on antimicrobial and biocompatible aspects, the principles of using hard nanomaterials (e.g., ceramic nanoparticles like TiO_2, aluminum oxide, or silica, or diamond-like carbon coatings) to increase surface hardness and wear resistance are well-established in materials science and applicable here [21, 22].

Improving biocompatibility for skin contact

Components of the handheld device that directly contact the user's skin, such as the main body, handles, or areas surrounding the mobilization/stimulation elements, must be biocompatible to prevent adverse skin reactions like irritation, inflammation, or allergic sensitization [22]. Nanocoatings can serve as an effective interface layer, masking potentially reactive underlying materials and presenting a biologically inert surface to the skin [21].

Materials suitable for biocompatible nanocoatings include specific medical-grade polymers applied as thin films or naturally derived biocompatible materials like chitosan. Polymers like polyvinyl alcohol have been investigated for biomedical applications, though sometimes requiring modification (e.g., with gelatin) to improve cell interaction if needed for specific applications beyond simple barrier function. The coating process must ensure uniformity and strong adhesion to prevent delamination and exposure of the substrate material. Rigorous testing according to ISO 10993 standards (particularly parts 5 for cytotoxicity and 10/23 for irritation and sensitization) is essential to validate the biocompatibility of the final coated surface [21].

Mechanisms and coating techniques

A variety of techniques can be employed to deposit nanocoatings onto medical device components, chosen based on the substrate material, the coating material, and the desired coating properties (thickness, uniformity, and adhesion) [21].

- Physical vapor deposition: Techniques like sputtering are suitable for depositing thin films of metals or metal oxides.
- Chemical vapor deposition: Can be used for various materials, including carbon-based coatings.
- Sol-gel processing: Allows for the creation of ceramic or hybrid organic-inorganic coatings at relatively low temperatures, suitable for materials like chitosan-silica hybrids.
- Electrochemical deposition: Useful for coating conductive substrates with metal or metal oxide nanoparticles, such as zinc oxide.
- Wet chemical methods: Techniques like dip-coating, spin-coating, and spray coating are versatile for applying solutions or dispersions of nanomaterials (e.g., polymers, nanoparticles) onto various substrate shapes. Layer-by-layer assembly allows for building multilayer coatings with precise control over composition and thickness.
- Other methods: Pulsed laser deposition can deposit nanoparticle films, while microarc oxidation creates porous oxide layers on metals like titanium, which can be subsequently loaded with agents like chitosan. Sonochemical methods use ultrasound to aid deposition.

The choice of method impacts the coating's structure, adhesion, and ultimately its performance and durability. However, the increasing use of nanomaterials in coatings raises important safety and regulatory questions [21]. The potential for nanoparticles or ions to leach from the coating during use or cleaning needs careful assessment to ensure they do not reach toxic levels [28]. While nanomaterials often have different mechanisms of action than traditional antibiotics, the potential for bacteria to develop resistance over time remains a concern that requires monitoring [21, 28]. Furthermore, the environmental impact of manufacturing and disposing of nano-coated devices needs consideration. Current regulatory frameworks may not fully encompass the specific challenges posed by nanocoatings, necessitating thorough risk assessment, adherence to evolving guidelines, and potentially new testing standards before widespread clinical adoption [28]. This regulatory uncertainty, coupled with the need for extensive safety validation, represents significant consideration in the development timeline and cost for nano-coated medical devices [21, 28].

Results and Discussion

Summary of nanotechnology's role

The separation between mechanical therapies and nutritional science represents an outdated model of healthcare. This paper posits that the future of effective patient care lies in their synergistic integration. The calf muscle mobilizing device offers a robust solution to the critical challenge of maintaining circulatory health in immobile individuals. However, its therapeutic benefits can be profoundly amplified when combined with the precision, efficacy, and monitoring capabilities afforded by nanotechnology in the food and nutrition sector.

By leveraging nano-enabled delivery systems for targeted nutrition, ensuring food integrity with nano-coatings and biosensors, and closing the feedback loop with wearable biomarker sensors, we can create a holistic health ecosystem. This framework, which combines biomechanical support with a highly optimized and monitored nutritional regimen, has the potential to significantly improve recovery times, reduce complications, and empower both patients and clinicians with the tools for truly personalized healthcare management [29].

Nanotechnology holds significant transformative potential for the development of next-generation handheld electrical calf muscle mobilization devices. By strategically integrating various nanomaterials and nanotechnologies, it is feasible to overcome many limitations of current approaches and create a device with substantially enhanced performance, functionality, and user experience. Nanomaterials can provide lightweight, durable construction suitable for a portable format. Nanocoatings can impart crucial surface properties like

antimicrobial activity, wear resistance, and biocompatibility. Nanosensors enable real-time, personalized monitoring of therapy and physiological response. Nanotechnology-driven transdermal drug delivery offers a complementary therapeutic modality for localized pain and inflammation management. Nano-enhanced electrical components can improve the efficiency and comfort of stimulation functions, while nano-enabled batteries and energy harvesting can revolutionize device power and autonomy. Finally, self-healing nanomaterials offer a path towards unprecedented device longevity and reliability. The synergistic combination of these advancements could lead to a paradigm shift in how calf muscle conditions are managed in both clinical and home settings [30].

Actionable recommendations for R&D focus

To bridge the gap between the potential demonstrated in research and a viable clinical product, focused research and development efforts are recommended in the following areas:

- Scalable integration and fabrication: Prioritize research into developing and validating scalable, cost-effective manufacturing techniques for reliably integrating flexibility into biocompatible, potentially flexible, device structures. This includes refining printing processes (screen, inkjet) for nanomaterial inks on relevant substrates (polymers, textiles) and ensuring robust interconnections.
- Energy harvesting and power management: Investigate and optimize robust energy harvesting solutions (particularly mechanical piezoelectric nanogenerators/ triboelectric nanogenerators leveraging mobilization motion) tailored to the specific energy demands and usage patterns of the handheld device. Develop efficient, miniaturized power management circuits capable of handling low and intermittent harvested power, potentially integrating micro-supercapacitors for energy buffering [31].
- Biocompatibility and safety validation: Conduct comprehensive, long-term biocompatibility and safety assessments (cytotoxicity, irritation, sensitization, genotoxicity, systemic effects, nanoparticle leaching) specifically for the nanomaterials (including functionalized variants and coatings) and integrated systems intended for prolonged or repeated skin contact in this device application. Studies should go beyond standard ISO 10993 tests where appropriate, considering the unique aspects of nanomaterials.
- System-level synergy and interference: Perform system-level studies to evaluate the synergistic effects and potential interferences when combining multiple modalities (e.g., mechanical mobilization, electrical stimulation, sensing, drug delivery). Assess factors like electromagnetic interference between components, thermal management, and the impact of one modality on the performance of another.
- Optimized self-healing materials: Develop self-healing polymer nanocomposites that strike an optimal balance between high healing efficiency (both mechanical and electrical, where applicable) and the necessary initial mechanical durability (strength, stiffness, wear resistance) required for specific device components. Focus on triggers compatible with device operation (e.g., low-voltage Joule heating) and repeatable healing cycles.

Regulatory strategy

Engage with regulatory agencies (e.g., U.S. Food and Drug Administration, European Medicines Agency) early in the development process to understand and address the specific requirements and potential challenges associated with gaining approval for a complex, nanotechnology-enabled combination medical device [32].

Roadmap

Phase–1: Material optimization and fabrication (year 0 - 1): Focus on scalable, cost-effective manufacturing of CNT/ graphene composites and biocompatible nanocoatings. Target: Achieve cost reduction of nanomaterials and develop robust coating processes capable of uniform deposition over surfaces.

Phase-2: Sensor and bioactive delivery system development (year 1 - 1.5): Refine multi-modal nanosensors for key biomarkers (e.g., lactate, glucose) with clinical accuracy and develop transdermal nanocarriers for nutraceuticals.

Phase-3: Integrated prototype and pre-clinical testing (year 1.5 - 2): Develop functional prototypes demonstrating integrated performance.

Phase-4: Clinical validation and regulatory pathway (year 2 - 2.5): Initiate small-scale human trials and engage regulatory bodies. Target: Demonstrate safety and efficacy in human subjects, achieving significant improvements in muscle recovery time or DVT prevention comparable to or exceeding current clinical standards.

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None.

Conflict of Interest

None.

References

1. McClements DJ, Rao J. 2011. Food-grade nanoemulsions: formulation, fabrication, properties, performance, biological fate, and potential toxicity. *Crit Rev Food Sci Nutr* 51(4): 285–330. https://doi.org/10.1080/10408398.2011.559558
2. Kakkos SK, Caprini JA, Geroulakos G, Nicolaides AN, Stansby G, et al. 2016. Combined intermittent pneumatic leg compression and pharmacological prophylaxis for prevention of venous thromboembolism. *Cochrane Database Syst Rev* 9(9): 1-73. https://doi.org/10.1002/14651858.cd005258.pub3
3. Formenti P, Menozzi A, Sabbatini G, Gotti M, Galimberti A, et al. 2025. Combined effects of early mobilization and nutrition on ICU-acquired weakness. *Nutrients* 17(6): 1073. https://doi.org/10.3390/nu17061073
4. Acosta E. 2009. Bioavailability of nanoparticles in nutrient and nutraceutical delivery. *Curr Opin Colloid Interface Sci* 14(1): 3–15. https://doi.org/10.1016/j.cocis.2008.01.002.

5. Williams KJ, Ayekoloye O, Moore HM, Davies AH. 2014. The calf muscle pump revisited. *J Vasc Surg Venous Lymphat Disord* 2(3): 329-334. https://doi.org/10.1016/j.jvsv.2013.10.053
6. DiGiovanni CW, Kuo R, Tejwani N, Price R, Hansen STJ, et al. 2002. Isolated gastrocnemius tightness. *J Bone Joint Surg Am* 84(6): 962-970. https://doi.org/10.2106/00004623-200206000-00010
7. Rathleff MS, Mølgaard CM, Fredberg U, Kaalund N, Andersen KB, et al. 2015. High-load strength training improves outcome in patients with plantar fasciitis: a randomized controlled trial with 12-month follow-up. *Scand J Med Sci Sports* 25(3): e292-e300. https://doi.org/10.1111/sms.12313
8. Xie L, Zhang Z, Wu Q, Gao Z, Mi G, et al. 2023. Intelligent wearable devices based on nanomaterials and nanostructures for healthcare. *Nanoscale* 15(2): 405-433. https://doi.org/10.1039/d2nr04551f
9. Xu Y, Li Y, Chai Z, Tao Y, Lin H, et al. 2025. Effectiveness of neuromuscular electrical stimulation in preventing venous thromboembolism: a meta-analysis based on randomized controlled trials. *Clin Appl Thromb Hemost* 31: 1-16. https://doi.org/10.1177/10760296251366423
10. Salata O. 2004. Applications of nanoparticles in biology and medicine. *J Nanobiotechnology* 2(1): 1-6. https://doi.org/10.1186/1477-3155-2-3
11. Sekhon BS. 2010. Food nanotechnology – an overview. *Nanotechnol Sci Appl* 3: 1–15. https://doi.org/10.2147/NSA.S8677
12. Young RJ, Kinloch IA, Gong L, Novoselov KS. 2012. The mechanics of graphene nanocomposites: a review. *Comp Sci Technol* 72(12): 1459-1476. https://doi.org/10.1016/j.compscitech.2012.05.005
13. Gao W, Emaminejad S, Nyein HYY, Challa S, Chen K, et al. 2016. Fully integrated wearable sensor arrays for multiplexed *in situ* perspiration analysis. *Nature* 529(7587): 509-514. https://doi.org/10.1038/nature16521
14. Kuswandi B, Damayanti F, Jayus J, Abdullah A, Heng LY. 2015. Simple and low-cost on-package sticker sensor based on litmus paper for real-time monitoring of beef freshness. *J Math Fund Sci* 47(3): 236–251. https://doi.org/10.1016/j.jfoodeng.2010.12.003
15. Mohanty C, Sahoo SK. 2010. The *in vitro* stability and *in vivo* pharmacokinetics of curcumin prepared as an aqueous nanoparticulate formulation. *Biomaterials* 31(25): 6597–6611. https://doi.org/10.1016/j.biomaterials.2010.04.062
16. Chen Y, Lu Y, Lee RJ, Xiang G. 2020. Nano encapsulated curcumin: and its potential for biomedical applications. *Int J Nanomedicine* 15: 3099-3120. https://doi.org/10.2147/ijn.s210320
17. Huang Q, Yu H, Ru Q. 2010. Bioavailability and delivery of nutraceuticals using nanotechnology. *J Food Sci* 75(1): R50–R57. https://doi.org/10.1111/j.1750-3841.2009.01457.x
18. Maiti D, Tong X, Mou X, Yang K. 2019. Carbon-based nanomaterials for biomedical applications: a recent study. *Front Pharmacol* 9: 1-16. https://doi.org/10.3389/fphar.2018.01401
19. Houghton DE, Ashrani A, Liedl D, Mehta RA, Hodge DO, et al. 2021. Reduced calf muscle pump function is a risk factor for venous thromboembolism: a population-based cohort study. *Blood* 137(23): 3284-3290. https://doi.org/10.1182/blood.2020010231
20. Sozer N, Kokini JL. 2009. Nanotechnology and its applications in the food sector. *Trends Biotechnol* 27(2): 82–89. https://doi.org/10.1016/j.tibtech.2008.10.010
21. Ezhilarasi PN, Karthik P, Chhanwal N, Anandharamakrishnan C. 2013. Nanoencapsulation techniques for food bioactive components: a review. *Food Bioprocess Technol* 6(3): 628–647. https://doi.org/10.1007/s11947-012-0944-0
22. Handford CE, Dean M, Henchion M, Spence M, Elliott CT, et al. 2014. Implications of nanotechnology for the agri-food industry: opportunities, benefits and risks. *Trends Food Sci Technol* 40(2): 226–241. https://doi.org/10.1016/j.tifs.2014.09.007
23. Gao W, Ota H, Kiriya D, Takei K, Javey A. 2019. Flexible electronics toward wearable sensing. *Acc Chem Res* 52(3): 523–533. https://doi.org/10.1021/acs.accounts.8b00500
24. Seil JT, Webster TJ. 2012. Antimicrobial applications of nanotechnology: methods and literature. *Int J Nanomedicine* 7: 2767-2781. https://doi.org/10.2147/ijn.s24805
25. Cha SH, Hong J, McGuffie M, Yeom B, VanEpps JS, et al. 2015. Shape-dependent biomimetic inhibition of enzyme by nanoparticles and their antibacterial activity. *ACS Nano* 9(9): 9097–9105. https://doi.org/10.1021/acsnano.5b03247
26. Duncan TV. 2011. Applications of nanotechnology in food packaging and food safety: barrier materials, antimicrobials and sensors. *J Colloid Interface Sci* 363(1): 1–24. https://doi.org/10.1016/j.jcis.2011.07.017
27. Silvestre C, Duraccio D, Cimmino S. 2011. Food packaging based on polymer nanomaterials. *Prog Polym Sci* 36(12): 1766–1782. https://doi.org/10.1016/j.progpolymsci.2011.02.003
28. Ravichandran R. 2010. Nanotechnology applications in food and food processing: innovative green approaches, opportunities and uncertainties for global market. *Int J Green Nanotechnol Phys Chem* 1(2): 72–96. https://doi.org/10.1080/19430871003684440
29. Heikenfeld J, Jajack A, Rogers J, Gutruf P, Tian L, et al. 2018. Wearable sensors: modalities, challenges, and prospects. *Lab Chip* 18(2): 217-248. https://doi.org/10.1039/c7lc00914c
30. Rhim JW, Park HM, Ha CS. 2013. Bio-nanocomposites for food packaging applications. *Prog Polym Sci* 38(10–11): 1629–1652. https://doi.org/10.1016/j.progpolymsci.2013.05.008
31. Oomen AG, Steinhäuser KG, Bleeker EAJ, van Broekhuizen F, Sips A, et al. 2018. Risk assessment frameworks for nanomaterials: scope, link to regulations, applicability, and outline for future directions in view of needed increase in efficiency. *NanoImpact* 9: 1-13. https://doi.org/10.1016/j.impact.2017.09.001
32. Weiss J, Takhistov P, McClements DJ. 2006. Functional materials in food nanotechnology. *J Food Sci* 71(9): R107–R116. https://doi.org/10.1111/j.1750-3841.2006.00195.x