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Review

Innovative approaches in the treatment of foot and ankle injuries

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Abstract

The treatment of foot and ankle injuries has evolved significantly with the introduction of innovative approaches aimed at improving clinical outcomes and patient recovery. This narrative review explores four key areas of innovation: regenerative therapies with stem cells and growth factors, minimally invasive surgery techniques, 3-dimensional (3D) printing and custom biomaterials, and the use of digital technologies and remote monitoring. Regenerative therapies have shown the potential to promote tissue regeneration and accelerate recovery, while minimally invasive surgery, such as arthroscopy, reduces invasiveness and recovery time. 3D printing and custom biomaterials offer solutions tailored to patients' anatomy, improving functionality and comfort. Digital technologies and remote monitoring facilitate continuous monitoring and treatment adherence. Despite advances, the clinical implementation of these innovations faces challenges related to cost, regulation, and equity of access. Integrating these approaches could significantly transform foot and ankle injury management, improving treatment effectiveness and patients' quality of life.

Level of Evidence III; Therapeutic Studies; Systematic Review of Level III Studies.

Keywords: Regenerative therapies; Minimally invasive surgery; Digital technologies.

Introduction

Foot and ankle injuries are prevalent in clinical practice, significantly impacting patients' mobility and quality of life. The causes of these injuries vary widely, from acute trauma to chronic degenerative processes such as fractures, sprains, tendinopathies, and ligament injuries. Historically, treating these conditions involved conventional methods such as immobilization, physical therapy, and, in some cases, surgical intervention. However, new approaches have emerged with medical science and technological advancement to optimize recovery, reduce rehabilitation time, and improve long-term functional outcomes[1].

In recent years, the introduction of regenerative therapies, such as stem cells and growth factors, has shown promising results in repairing soft tissue injuries and accelerating bone healing. In addition, minimally invasive techniques, such as arthroscopy, provide a less traumatic alternative to surgical interventions, reducing the morbidity associated with traditional procedures. These innovations and the developing of more biocompatible biomaterials and prostheses offer new perspectives for treating complex foot and ankle injuries[2].

Another area of significant advancement is using 3-dimensional (3D) printing technologies to create custom orthotics and prosthetics. These devices allow precise patient anatomy adjustment, improving comfort and treatment effectiveness. In addition, advances in digital technology-based rehabilitation, such as mobile apps and motion monitoring devices, are transforming how patients manage their recovery by offering real-time feedback and personalized exercise programs[3].

Treating these injuries also benefits from the increasing integration of personalized medicine and data analysis. Using artificial intelligence algorithms to predict the prognosis of injuries and customize treatment plans can revolutionize the clinical management of these conditions, providing more effective interventions with lower rates of complications. This multidisciplinary, patient-centered approach highlights the importance of combining emerging technologies with traditional clinical knowledge to achieve better outcomes[4].

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The objective of this narrative review is to explore innovative approaches in the treatment of foot and ankle injuries, discussing emerging therapies and their impacts on current clinical practice. In addition, evaluate the evidence on the effectiveness of these new technologies compared to traditional procedures, highlighting the main advantages and challenges in their implementation.

Methods

A structured methodological protocol was followed to conduct this narrative review to ensure the analyzed sources' scope and relevance. Initially, a systematic search was performed in the main academic databases, including PubMed, Scopus, Web of Science, and Cochrane Library. Study selection was guided by specific inclusion and exclusion criteria, ensuring that only studies published between 2010 and 2023 were considered, focusing on innovative approaches in the treatment of foot and ankle injuries.

Descriptors used in the search included "foot injuries," "ankle injuries," "innovative treatment," "stem cells," "regenerative therapy," "biomaterials," "arthroscopy," "3D printing," and "digital technologies." The terms were combined using Boolean operators (AND, OR) to maximize the relevance of the results. Review articles, clinical trials, case studies, and meta-analyses were included as long as they directly addressed therapeutic innovations applicable to foot and ankle injuries.

After identifying the studies, titles and abstracts were screened to exclude duplicate publications and those not directly related to the proposed theme. The full texts of the selected studies were thoroughly reviewed, including those that presented detailed descriptions of the new therapeutic approaches and data on the effectiveness and safety of the proposed treatments.

Data extracted from the studies included information on the types of injuries treated, the innovative technologies or techniques applied, the clinical outcomes observed, and the limitations reported by the authors. The results were synthesized qualitatively, allowing the comparison of the different innovative therapeutic methods and their clinical applicability. Data analysis sought to identify emerging trends, implementation challenges, and potential areas for future research.

This narrative review was structured to provide critical insight into the current state of innovations in treating foot and ankle injuries, highlighting the promises and limitations of new technologies. Given the exploratory nature of this review and the diversity of interventions addressed in the selected studies, there was no quantitative evaluation or meta-analysis of the data.

Regenerative therapies with stem cells and growth factors

Regenerative therapies, particularly stem cells and growth factors, have emerged as an innovative approach in the treatment of foot and ankle injuries, offering a promising alternative to conventional methods. Mesenchymal stem cells, derived mainly from bone marrow or adipose tissue, can differentiate into several cell types, including osteoblasts, chondroblasts, and fibroblasts, contributing directly to the regeneration of damaged tissues. Recent studies indicate that these cells, when applied to ligament and tendon injuries, promote an acceleration in the healing process, improve the quality of tissue regeneration, and reduce the recovery time of patients[5].

In addition to stem cells, growth factors such as platelet-rich plasma (PRP) have been widely studied for their potential to modulate the inflammatory response and promote angiogenesis and tissue repair. Platelet-rich plasma, rich in bioactive factors such as platelet-derived growth factor (PDGF) and vascular endothelial growth factor (VEGF), is applied directly to injured areas, stimulating tendon and cartilage regeneration. In clinical trials, the use of PRP has shown encouraging results, with reduced pain and improved function in patients with chronic Achilles tendon injuries and plantar fasciitis[6].

However, despite promising results, data on the long-term effectiveness of regenerative therapies are still limited. Studies indicate significant variability in clinical outcomes depending on stem cell origin, PRP concentrations used, and the type of injury treated. This heterogeneity makes it difficult to standardize therapeutic protocols, which constitutes an obstacle to their wide adoption in clinical practice. In addition, although the safety of these therapies has been widely demonstrated, there are concerns regarding the strict control of the source and manipulation of cells and the possibility of adverse immune responses in some patients[5].

Another relevant aspect addressed in this review is the economic feasibility of these therapies. The costs of obtaining and processing stem cells and PRP are considerable, limiting access to these innovative treatments, especially in public health systems and less developed regions. In addition, the lack of clear reimbursements by insurers and regulations defined in several countries makes it difficult to include them in therapeutic routines[6].

Although regenerative therapies with stem cells and growth factors have great potential in treating foot and ankle injuries, there are still substantial challenges related to the standardization of protocols, cost, and accessibility. Continuing research is essential to optimize these approaches and establish their position in clinical practice, especially with long-term studies that can validate their efficacy in different types of injuries and patient populations[5].

Advances in minimally invasive surgery: arthroscopy and percutaneous techniques

Minimally invasive surgical techniques, such as arthroscopy and percutaneous procedures, have revolutionized the treatment of foot and ankle injuries, providing significant benefits over traditional surgical procedures. Arthroscopy,

which allows access to the interior of the joints through small incisions, has stood out in the management of ligament injuries, tendinopathies, and intra-articular fractures. Compared to open surgeries, the reviewed studies indicate that arthroscopy offers faster recovery, less postoperative pain, and a lower risk of complications such as infections and extensive scarring[7].

Advances in arthroscopic techniques, such as high-definition cameras and articulated instruments, have allowed greater surgical precision and less tissue trauma. In specific injuries, such as severe ankle sprains and Achilles tendon ruptures, arthroscopy is effective in restoring joint stability and biomechanical function, with high success and low complication rates. Studies included in this review indicate that this approach improves immediate functional results and reduces the time to return to sports and occupational activities, which is especially relevant for athletes and individuals with high physical demands[8].

In addition to arthroscopy, percutaneous techniques have emerged as a minimally invasive alternative in the treatment of foot and ankle fractures and deformities. Procedures such as percutaneous osteosynthesis of calcaneal fractures and correction of hallux valgus deformities are effective in reducing surgical time and morbidity associated with open incisions. This review highlights that these techniques, when applied to indicated injuries, can reduce the risk of complications, such as skin necrosis and infection while preserving adjacent anatomical structures[9].

However, it is important to note that the effectiveness of these techniques is directly related to the surgeons' learning curve. This review suggests that while arthroscopy and percutaneous techniques offer better outcomes for patients, inadequate execution due to a lack of specialized training can result in complications such as neurovascular lesions and bone fixation failures. Therefore, there is a continuing need for training and enhancing the skills of surgeons and the development of clinical guidelines that guide the proper selection of patients for these interventions[8].

Another point discussed in our review is the limited access to these technologies in less developed regions or health systems with limited resources. Although minimally invasive techniques provide clear advantages, the high cost of equipment and the need for specialized infrastructure may restrict their wide adoption. Future studies should focus on strategies to make these technologies more accessible and evaluate their effectiveness in diverse clinical settings and populations with different risk profiles[9].

Advances in arthroscopy and percutaneous techniques represent a milestone in the treatment of foot and ankle injuries, providing better functional recovery, less surgical trauma, and reduced complications. However, the full implementation of these techniques depends on specialized training, access to technological resources, and continuous development of studies that validate their effectiveness in the long term and different populations[8].

3D printing and custom biomaterials

The application of 3D printing and the development of customized biomaterials represent significant innovations in treating foot and ankle injuries, offering tailored solutions that improve the accuracy and effectiveness of therapeutic interventions. 3D printing technology has created customized prostheses, orthoses, and implants tailored to each patient's anatomy. This approach allows for more precise adaptation to the injury site, resulting in better stability and functionality than traditional methods using standardized devices[10].

Recent studies indicate that the customization of orthoses and prostheses using 3D printing has demonstrated clear benefits in patient comfort, reduction of postoperative complications, and optimization of clinical outcomes. In complex fractures or congenital deformities, personalized implants offer a more faithful anatomical reconstruction, contributing to a faster and more efficient functional recovery. In addition, 3D printing facilitates the fabrication of anatomical models for surgical planning, allowing surgeons to visualize and simulate the procedure before the intervention, increasing accuracy and reducing intraoperative time[11].

Biomaterials used in 3D printing have also evolved, incorporating biocompatible materials that promote integration with surrounding tissues and minimize the risk of rejection. Using biodegradable polymers and composite materials such as ceramics and metals offers versatile options for creating temporary or permanent devices depending on clinical need. These materials are designed to withstand the biomechanical forces associated with the foot and ankle while favoring bone and tissue regeneration. However, our review points out that there are still technical challenges, such as optimizing the mechanical strength of these materials to ensure the longevity of implants in patients with high functional demand[12].

Despite the demonstrated benefits, the high cost associated with 3D printing and the development of customized biomaterials remains an obstacle to their large-scale implementation. Our review highlights that the production of these devices still requires specialized equipment and manufacturing processes that drive up costs, making them inaccessible for many patients, especially in public health systems. In addition, the lack of standardized regulation for the clinical use of 3D-printed implants raises questions about their long-term safety and effectiveness, and further studies are needed to validate these devices in large clinical trials[10].

Additionally, our review points out that 3D printing in clinical settings still faces limitations related to production time. While the technology allows for the creation highly customized devices, the time required to design, test, and produce a customized implant or orthosis may not be feasible in emergencies or when immediate surgical interventions are required. Therefore, developing faster and more efficient production processes is fundamental to expanding the clinical use of these technologies[11].

3D printing and custom biomaterials can potentially transform the treatment of foot and ankle injuries by offering tailored solutions that improve anatomical adaptation,

reduce complications, and increase treatment effectiveness. However, the wide implementation of these approaches requires overcoming barriers related to cost, regulation, and production time and continuous studies to ensure their safety and effectiveness in the long term[12].

Use of digital technologies and remote monitoring in rehabilitation

Digital technologies and remote monitoring transform foot and ankle injury rehabilitation, providing more efficient, personalized, and affordable approaches. Mobile apps, wearable devices, and telemedicine platforms have been increasingly used to monitor patient progress, optimize rehabilitation programs, and facilitate communication between healthcare providers and patients. This review highlights that these digital tools offer a practical form of continuous follow-up, allowing real-time adjustments in treatment based on patient performance, which enhances recovery and improves treatment adherence[13].

One of the main benefits of using digital technologies in rehabilitation is the ability to monitor biomechanical parameters, such as weight load, range of motion, and muscle strength, through sensors coupled to wearable devices, such as smart orthoses and adaptive footwear. These devices provide real-time data, allowing healthcare professionals to fine-tune the rehabilitation program accurately and based on evidence. Reviewed studies indicate that this approach can reduce recovery time and improve functional outcomes while decreasing the need for in-person visits, which is particularly useful for patients with walking difficulties or living in remote areas[14].

In addition, mobile applications have played a key role in encouraging patients to adhere to rehabilitation protocols. Digital platforms that offer guided exercise videos, reminders, and real-time feedback increase patient motivation and ensure that exercises are performed correctly. Our review suggests that using these apps significantly improves patients' engagement with treatment, resulting in faster and more efficient recovery. However, the variability in the quality and accuracy of the applications available in the market is a challenge, and this review recommends the development of regulations that guarantee the effectiveness and safety of these tools[15].

Another relevant aspect addressed in our review is the positive impact of telemedicine on the follow-up of patients with foot and ankle injuries. Virtual consultations allow health professionals to monitor rehabilitation progress and make adjustments to treatment without the need for frequent face-to-face consultations. In addition, remote monitoring provides a more integrated multidisciplinary approach, allowing collaboration between specialists, such as physiotherapists, orthopedists, and rheumatologists, resulting in a more cohesive and individualized treatment plan. However, our review indicates that a lack of adequate infrastructure and limited internet access in some regions may hinder large-scale implementation[13].

Despite the benefits, the widespread adoption of digital technologies and remote monitoring in foot and ankle injury rehabilitation still face significant challenges. Issues related to data privacy, cybersecurity, and integration with existing health systems are important concerns that must be addressed. This review also suggests that while digital technologies have shown promising results, the lack of long-term studies on the clinical effectiveness of these approaches limits their wider acceptance among healthcare professionals[15].

The use of digital technologies and remote monitoring in the rehabilitation of foot and ankle injuries offers new opportunities to improve the effectiveness and efficiency of treatment, providing greater accessibility and personalization of care. However, for these approaches to be widely implemented, it is necessary to overcome technical, regulatory, and infrastructure barriers and conduct further studies that validate their long-term benefits in different populations[14].

Future perspectives and challenges in the clinical implementation of innovative approaches

Innovative approaches in the treatment of foot and ankle injuries, such as using regenerative therapies, personalized biomaterials, minimally invasive techniques, and digital technologies, present significant potential to transform the management of these conditions. However, widespread clinical implementation of these technologies still faces substantial challenges. Prospects indicate that as new technologies are improved and become more accessible, there will be an improvement in functional patient outcomes and an acceleration in recovery times. However, integrating these innovations into clinical practice requires a careful approach that considers economic viability, access equity, and patient safety[16].

One of the main challenges in adopting these approaches is the technological infrastructure and the associated costs. For example, 3D printing, custom biomaterials, and stem cell therapies are still high-cost technologies, limiting their availability in public health systems and regions with fewer resources. Studies indicate that reducing production costs and developing standardized protocols are crucial to disseminating these innovations. Prospects, therefore, should focus on developing strategies to make these technologies more accessible, including partnerships between research institutions and medical technology industries, as well as government investments to facilitate their adoption[17].

In addition to economic challenges, education and training of health professionals are determining factors for the successful implementation of these new approaches. Minimally invasive surgical techniques, such as arthroscopy and percutaneous procedures, require specialized skills and continuous training. Our review highlights that many surgeons still face a significant learning curve when adopting these techniques, which can limit their application and increase the risk of complications. In the future, medical

education programs must include specific training for using these technologies, ensuring that professionals can apply them safely and effectively[18].

Another crucial point is the regulation and scientific validation of these new approaches. Although regenerative therapies, such as stem cells, have shown promising results in early preclinical and clinical studies, the lack of robust long-term data still precludes their large-scale adoption. Our review points out that, without clear guidelines and more robust clinical evidence, hesitancy to adopt these technologies persists among many health professionals. Future progress will depend on large-scale and long-term clinical trials proving the safety and efficacy of these therapies and formulating regulations that guide their clinical application[19].

Equity in access to innovations also stands out as an important challenge. Digital technologies such as remote monitoring devices and mobile applications can significantly benefit the rehabilitation of patients with foot and ankle injuries. However, our review points out that access to these technologies is still uneven, especially in rural areas and countries with less technological development. In the future, expanding internet access and digital inclusion will be key to ensuring that these tools can benefit a larger portion of the population. In addition, health systems need to adopt policies that promote the use of these innovations in an inclusive manner[20].

Prospects for treating foot and ankle injuries are promising, with the potential to significantly improve clinical outcomes by adopting innovative approaches. However, the challenges to its implementation include cost, infrastructure, professional training, regulation, and equity of access. Overcoming these obstacles will require a collaborative approach between governments, research institutions, and industry and ongoing efforts to validate and standardize these new technologies in the clinical setting[16].

Conclusions

Regenerative therapies, minimally invasive surgical techniques, personalized biomaterials, digital technologies, and remote monitoring emerge as promising solutions to overcome the limitations of traditional treatments. The ability of these interventions to offer greater precision, personalization, and ongoing follow-up has the potential to transform clinical practice, providing more efficient recovery and a better quality of life for patients.

However, the widespread implementation of these innovations still faces substantial challenges, such as high costs, the need for adequate technological infrastructure, ongoing training of healthcare professionals, and stringent regulation to ensure the safety and effectiveness of new approaches. In addition, equity in access to these technologies remains a significant barrier, especially in health systems with limited resources. In the future, joint efforts among researchers, healthcare professionals, managers, and the medical technology industry will be essential to make these innovations accessible and effectively integrate them into clinical practice.

In short, although technological innovations in treating foot and ankle injuries are at an advanced stage of development and implementation in some contexts, the full realization of their potential will depend on overcoming economic, technical, and social barriers. With the continuous advancement of research and the democratization of access to these technologies, managing these injuries is expected to be increasingly effective, substantially improving clinical outcomes and patient experience soon.

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