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Edited by Md Enamul Hoque



Rehabilitation Engineering - Advances and Applications

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Contributors

Amit K. Vimal, Anoop Kant Godiyal, Chanelle Ribeiro-Wagener, Călin Corciovă, Cătălina Luca, Ilie Onu, Jun Wu, Luiz Philipe Molina Vana, Md Enamul Hoque, Md Sakif Zawad, Nur Md Atiquzzaman Rasel, Robert Fuior, Shivani Sharma, Terry Jeremy Ellapen, Yvonne Paul

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Biomedical Engineering

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Aims and Scope of the Series

Biomedical Engineering is one of the fastest-growing interdisciplinary branches of science and industry. The combination of electronics and computer science with biology and medicine has improved patient diagnosis, reduced rehabilitation time, and helped to facilitate a better quality of life. Nowadays, all medical imaging devices, medical instruments, or new laboratory techniques result from the cooperation of specialists in various fields. The series of Biomedical Engineering books covers such areas of knowledge as chemistry, physics, electronics, medicine, and biology. This series is intended for doctors, engineers, and scientists involved in biomedical engineering or those wanting to start working in this field.

Meet the Series Editor



Robert Koprowski, MD (1997), Ph.D. (2003), Habilitation (2015), is an employee of the University of Silesia, Poland, Institute of Computer Science, Department of Biomedical Computer Systems. For 20 years, he has studied the analysis and processing of biomedical images, emphasizing the full automation of measurement for a large inter-individual variability of patients. Dr. Koprowski has authored more than a hundred research papers with dozens in impact factor (IF) journals and has authored or co-authored six books. Additionally, he is the author of several national and international patents in the field of biomedical devices and imaging. Since 2011, he has been a reviewer of grants and projects (including EU projects) in biomedical engineering.

Meet the Volume Editor



Prof. Dr. Md Enamul Hoque is a Professor in the Department of Mechanical Engineering, Faculty of Engineering, at the University of Tabuk, Saudi Arabia. Prior to joining the University of Tabuk, he held senior academic and leadership positions at internationally reputed institutions, including Professor of Biomedical Engineering at the Military Institute of Science and Technology (MIST), Dhaka, Bangladesh; Head of the Department of Biomedical Engineering at King Faisal University, Saudi Arabia; and Founding Head of the Bio-engineering Division at the University of Nottingham Malaysia Campus. He earned his Ph.D. from the National University of Singapore and a Postgraduate Certificate in Higher Education from the University of Nottingham, UK. Recognized as one of the Top 2% Scientists in the World, Prof. Hoque's research spans additive manufacturing, biomaterials, nanomaterials, rehabilitation engineering, and translational research, with a strong emphasis on sustainability and the circular economy. He has published extensively in high-impact journals and actively contributes to academic leadership, international research collaboration, and innovation-driven education.

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Preface

Rehabilitation Engineering lies at the convergence of engineering, health sciences, and human-centered design. As global populations age and the incidence of chronic and disabling conditions continues to rise, the need for innovative, effective, and accessible rehabilitation solutions has become increasingly urgent. *Rehabilitation Engineering – Advances and Applications* provides a comprehensive and timely examination of the technologies and methodologies that are redefining contemporary rehabilitation practice.

This edited volume brings together contributions from leading researchers, clinicians, and engineers worldwide. It encompasses both foundational principles and state-of-the-art developments across a broad range of topics, including assistive devices, rehabilitation robotics, wearable and sensor-based systems, human-machine interfaces, and data-driven therapeutic approaches. Beyond technological innovation, the chapters critically address clinical integration, usability, ethical considerations, and real-world implementation, offering readers a balanced perspective that bridges theory and practice.

The organization of the book reflects a deliberate progression from fundamental concepts to transformative applications. Initial chapters establish the theoretical framework of rehabilitation engineering, outlining key definitions, methodologies, and its evolving role within modern healthcare systems. Subsequent sections explore advanced research findings, interdisciplinary case studies, and emerging technologies that demonstrate how engineering solutions can enhance functional recovery, independence, and quality of life for individuals with physical and cognitive impairments.

A unifying theme throughout the volume is the centrality of the human experience. While technological advancement is essential, the ultimate objective of rehabilitation engineering is to empower individuals, restore autonomy, and promote inclusion. Accordingly, each chapter emphasizes user-centered design, safety, accessibility, and collaborative engagement among patients, caregivers, clinicians, and technologists.

Rehabilitation Engineering – Advances and Applications is intended for a broad readership, including graduate students seeking a solid foundation in the field, researchers exploring current trends and future directions, clinicians interested in emerging rehabilitation tools, and professionals involved in the design and deployment of rehabilitation technologies.

We hope that this book stimulates inquiry, inspires innovation, and makes a meaningful contribution to the advancement of rehabilitation science and practice. The editor gratefully acknowledges the authors for their scholarly contributions, the peer reviewers for their constructive and rigorous evaluations, and the readers who share a commitment to advancing rehabilitation through engineering excellence.

Md Enamul Hoque

Faculty of Engineering,
Department of Mechanical Engineering,
University of Tabuk,
Tabuk, Saudi Arabia

*Department of Biomedical Engineering,
Military Institute of Science and Technology,
Dhaka, Bangladesh

* Work was primarily conducted at the Department of Biomedical Engineering, Military Institute of Science and Technology, Dhaka, Bangladesh

Emerging Technologies in Assistive Devices: Shaping the Future of Rehabilitation Engineering

Călin Corciovă, Robert Fuior, Ilie Onu and Cătălina Luca

Abstract

Assistive devices in rehabilitation engineering are essential for enhancing the quality of life for individuals with disabilities by supporting their mobility, communication, and daily activities. Recent advancements in robotics, artificial intelligence, and biomedical engineering have led to significant innovations in this field. This chapter explores key technologies and developments in assistive and rehabilitation devices. Robotic exoskeletons, wearable devices designed to assist or augment limb and body movement, benefit individuals with spinal cord injuries, stroke, or conditions like cerebral palsy. Brain-computer interfaces (BCIs) enable those with severe motor impairments, such as amyotrophic lateral sclerosis (ALS) or quadriplegia, to control devices using brain signals alone. Virtual reality (VR) and augmented reality (AR) are increasingly used in therapy, providing interactive, controlled environments where patients can practice movements and cognitive tasks. Additionally, Artificial Intelligence (AI) and Machine Learning (ML) contribute to rehabilitation by personalizing therapy, analyzing movement patterns, and predicting recovery progress. These innovative technologies make assistive devices more intuitive, accessible, and cost-effective, improving rehabilitation outcomes.

Keywords: rehabilitation engineering, assistive technology, personalized medicine, sensory substitution, innovation

1. Introduction

In the digital age, engineering plays a key role in the development of assistive technologies, providing innovative solutions to improve the lives of people with disabilities and facilitate their integration into society. Assistive engineering combines principles from diverse fields, such as biomedical engineering, robotics, artificial intelligence, and ergonomic design, to create devices and systems that support users' mobility, communication, and independence.

From robotic exoskeletons and smart prosthetics to accessibility software and alternative communication devices, assistive engineering offers a diverse range of technologies designed to reduce the barriers faced by people with disabilities. Recent

advances in fields such as artificial intelligence, 3D printing, and neuroengineering open new perspectives for creating more personalized and effective solutions.

Engineering contributes to assistive technologies in several key areas:

Biomedical engineering – develops advanced prosthetics, neural implants, and medical devices for rehabilitation and assistance.

Robotics and mechatronics – create exoskeletons, smart wheelchairs, and robotic assistance systems for people with reduced mobility.

Artificial intelligence and machine learning – enables the development of voice assistants, intelligent screen readers, and image recognition systems for the blind.

Software engineering and digital accessibility – develops user-friendly interfaces for users with disabilities, text-to-speech applications, and alternative control technologies (e.g. eye control).

3D printing and nanotechnology – facilitates the production of personalized prostheses, orthopedic devices, and innovative materials for medical rehabilitation.

As technology evolves, assistive technology is becoming more personalized, efficient, and accessible. Artificial intelligence, nanotechnology, and bioengineering will continue to transform the field, creating solutions that adapt to the individual needs of users. The future of assistive technology depends on the collaboration of engineers, doctors, designers, and users to ensure the development of solutions that truly improve the lives of people with disabilities. Thus, engineering is not only revolutionizing the field of assistive technology but also contributing to building a more inclusive and accessible world for all.

2. Virtual reality in rehabilitation engineering: Transforming therapy and recovery

2.1 Short history of virtual reality

The history of virtual reality (VR) is indeed an exciting one and reflects a constant evolution of technology and human imagination. As early as the 1930s, the concept of VR began to be explored in literature, and later, the first practical attempts to bring the idea to reality [1]. An early reference point is the story “Pygmalion’s Spectacles” by Stanley G. Weinbaum, published in 1935. It described a device capable of providing users with immersive sensory experiences, anticipating in a visionary way the fundamental elements of VR: visual, auditory, and narrative simulation. This story laid the foundations for the idea of VR, even if the term itself was used much later [2].

Another key moment in the evolution of VR came in 1957 with the invention of the “Sensorama” by Morton Heilig. This device was a true technological breakthrough, providing users with visual, auditory, olfactory, and tactile sensations to simulate realistic experiences. Although “Sensorama” was not conceived as a wearable device, it was the forerunner of modern VR technologies and demonstrated for the first time the immersive potential of this technology [3, 4]. These defining moments demonstrate that, from its inception, VR was seen to extend human perception and transform interaction with the environment. The continued exploration and development of technology has opened numerous possibilities in areas such as entertainment, medicine, education, and scientific research.

Ivan Es. Sutherland is absolutely a towering determine withinside the records of technology, being taken into consideration the “figure of pics for your computer. In 1965, he supplied an innovative imaginative and prescient of VR, describing the

concept of a „display screen that suggests a really perfect international” and laying the conceptual foundations of VR. This description, known as “The Ultimate Display,” predicted a computer-generated international that could not simply be seen, but was additionally skilled as tangible. The fruits of his paintings turned into a reality in 1968, while he created the primary practical VR tool, known as the Sword of Damocles. It consisted of a head-installed show related to a head-monitoring system, giving the person the feeling of immersion in a three-dimensional, computer-generated space. Although the tool turned into rudimentary, with a cumbersome layout suspended from the ceiling (for this reason, its symbolic name), it marked the start of a brand-new generation for immersive technologies. “Sword of Damocles” turned into a key second within the evolution of VR, introducing standards that are nevertheless used today, including monitoring the placement and actions of the person to modify the visible perspective. The basis for advanced development was set at some stage in this early stage, which performed a substantial position within the established order of VR as a studies discipline with a number of applications, including schooling simulations, scientific therapies, and entertainment [5].

In 1991, Jaron Lanier and Thomas G. Zimmerman, two influential figures in technology, founded The Virtual Reality Foundation, marking a pivotal moment in VR history. Lanier, credited with coining the term “virtual reality” and pioneering the development of early VR equipment, played a key role in shaping both the technological and conceptual framework of the field. Alongside Zimmerman, he championed the integration of VR across various industries, including education, medicine, and entertainment. One of the foundation’s greatest achievements was establishing a collaborative platform for researchers, engineers, and entrepreneurs, fostering a global ecosystem of VR innovation. Their efforts not only drove technological advancements but also made VR equipment more affordable, accelerating its widespread adoption [6–8].

The 1990s were a milestone in the popularization of VR technology, marking the debut of modern consumer VR devices. It was during this period that companies such as Sega and Nintendo took the first steps in bringing VR to the mass market, offering products that promised immersive experiences. A notable example is Virtual Boy, which was launched by Nintendo in 1995. It was the first significant attempt to bring VR into consumers’ homes through an affordable device. Virtual Boy used a monochromatic system based on red LEDs to create stereoscopic 3D images, giving users a sense of depth while playing. In parallel, Sega has been developing prototypes for devices such as Sega VR, which are designed for its game consoles. In addition, the trials in the 1990s demonstrated that VR had the potential to become more than a niche technology, foreshadowing its expansion into areas as diverse as gaming, education, and medicine [9].

After 2010, VR experienced a renaissance thanks to advances in mobile technology, the increased processing power of computers, and the miniaturization of electronic components. These advances have made it possible to develop affordable, high-performance, and easier-to-use VR devices, allowing consumers to experience VR in the comfort of their own homes. Companies such as Oculus, HTC, and Sony have played a significant role in this technological revolution. The launch of the Oculus Rift headset in 2016, which began as a Kickstarter project, marked a milestone in the VR industry. With an ergonomic design, precise motion tracking, and high graphics quality, the Oculus Rift redefined the standard for high-quality VR experiences. HTC, in partnership with Valve, launched the HTC Vive, another innovative device that introduced full 3D spatial tracking through intuitive base stations and

controllers, bringing more natural and immersive interaction. At the same time, Sony entered the VR market in a big way with PlayStation VR for PlayStation 4 consoles, making VR technology accessible to a wide audience of gamers [4, 10–12].

The advancement of VR technology has generated other related technologies that extend and enrich the interaction between users and their environment, such as augmented reality (AR) and mixed reality (MR). These concepts have redefined the way we perceive and interact with the real world, adding new digital layers of information and experiences. AR, which superimposes virtual elements (images, sounds, or data) over the real world, has become known to the public through devices such as Google Glass. Despite being initially aimed at ordinary consumers, the project has since become useful in specialized fields like medicine, industry, and education. Mixed Reality (MR) is a combination of VR and AR that creates dynamic interactions between virtual and real objects. It was popularized by Microsoft through the HoloLens. HoloLens devices can make it possible to integrate digital objects into the physical world and interact with them in a natural way, which can be applied to design, architecture, surgery, and professional training [13, 14].

VR is now recognized as an advanced technology that enables users to interact with simulated environments in either two-dimensional (2D) or three-dimensional (3D) formats through specialized devices. The most common of these are VR headsets, which are worn on the head to create an immersive virtual experience. Users can use resolute controllers or joysticks to interact with these environments, allowing them to manipulate objects and navigate smoothly. To provide a VR experience that is responsive and intuitive, these devices are necessary, allowing for real-time feedback and precise control over movements in virtual space [15, 16]. Virtual reality applications are diverse and are expanding in various industries, including:

- *Gaming* – VR has transformed the gaming industry, offering an immersive experience that is unmatched in comparison to traditional games.
- *Education and training* – VR can be used in education and training to recreate real-world scenarios, such as surgical procedures or military exercises, using interactive learning simulations.
- *Medicine* – VR plays a role in rehabilitation therapies, medical procedure simulations, and even the diagnosis and treatment of certain conditions.
- *Architecture and design* – Professionals can develop and visualize 3D models of structures, enabling them to explore and refine designs before physical construction begins.
- *Tourism* – Virtual tours allow users to explore destinations remotely, providing a realistic experience of travel without leaving home (**Figure 1**).

VR is based on creating an artificial world where users can interact similarly to the real world, but in virtual environments. This is achieved through a human-computer connection, which allows for a detailed simulation of virtual environments and deep interaction with them. In this way, VR combines advanced computing technology with sensors that allow the perception of visual, auditory, tactile, and kinesthetic stimuli, providing a highly immersive experience [17]. Simulation, interaction, and immersion are the essential elements on which VR technology is based. Simulation

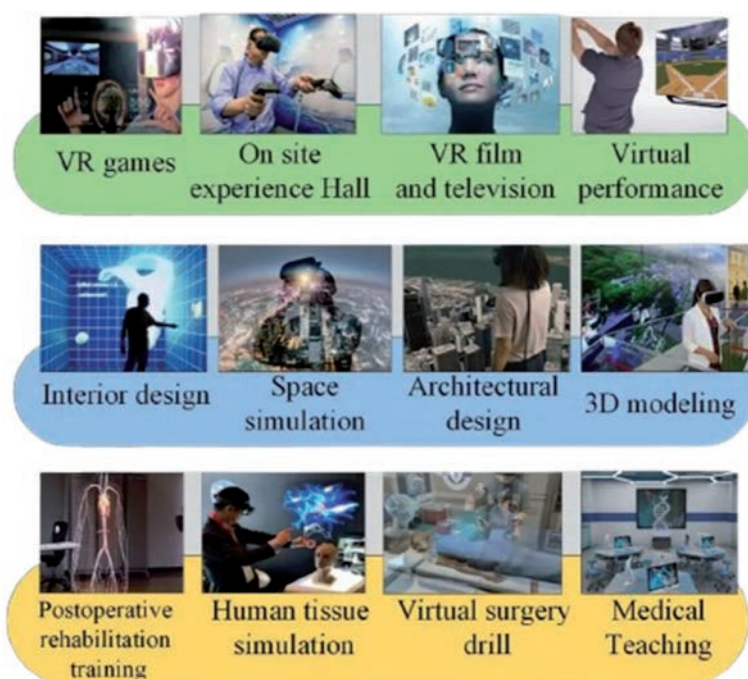


Figure 1.
 VR technology application field.

refers to the creation of a virtual environment that mimics reality or creates a completely new universe, while interaction is achieved through devices that allow users to manipulate objects, navigate, or communicate with elements in the virtual world. Immersion refers to the ability of technology to “lock” the user into a virtual environment, making them feel part of that environment. These elements enable intuitive interaction, where the user perceives stimuli in the virtual world through various senses, helping to make a deep emotional and cognitive connection with the virtual environment [18]. For example, visual and auditory stimuli create a sense of presence, while tactile and kinesthetic stimuli, through haptic devices, add a physical dimension to the experience. One of the significant advantages of VR is the ability to reduce the perception of pain and transform unpleasant experiences into more comfortable virtual environments. This is possible by connecting the cognitive and emotional centres of the nervous system, which are positively influenced by virtual stimuli. VR can be used for therapeutic purposes, for example, in pain management or rehabilitation to help patients cope with difficult or painful situations in a more controlled and comfortable way [19].

2.2 Virtual reality and rehabilitation engineering devices

The use of VR in rehabilitation is indeed gaining ground, supported by a growing body of scientific evidence highlighting its diverse applications. VR has shown promise in the rehabilitation of upper limb function after stroke. By using virtual environments that ask patients to perform specific motor tasks, VR can help improve movement coordination, motor learning, and neuroplasticity. Several studies have demonstrated significant improvements in functional outcomes for stroke patients

using VR-assisted rehabilitation. VR interventions have applications in musculo-skeletal rehabilitation such as joint and soft tissue injuries, post-surgical recovery, or chronic pain management. The immersive nature of VR helps to promote active engagement, improve joint mobility, and encourage repetitive exercise in a controlled and motivating environment [20].

A virtual reality (VR) system is a combination of hardware and software components that work together to create an immersive digital experience. The hardware component includes a VR headset (HMD—Head-Mounted Display) for stereoscopic images and head tracking, motion controllers for interaction, and external sensors such as cameras, infrared trackers, or LiDAR for precise motion detection [21]. A processing unit (PC, game console, or standalone VR system) powers the experience by rendering graphics and handling calculations. Haptic feedback devices, including gloves, vests, or full-body suits, simulate the sensations of touch, while a spatial audio system enhances immersion. The software component includes a VR engine (such as Unity or Unreal Engine) to create and render 3D environments, while tracking software processes motion data from the sensors. Middleware and SDKs (such as OpenVR, Oculus SDK, or SteamVR) provide APIs for hardware compatibility, and the operating system (Windows, macOS, Android) supports applications and drivers. VR applications and games provide interactive experiences, from entertainment to professional simulations, while cloud or network services enable multiplayer functionality, data synchronization, and content streaming (**Figure 2**).

Several different commercially available VR and MR devices are being used in rehabilitation. Each device is associated with a leading company in the field and offers a wide range of solutions for treatments in various medical conditions, such

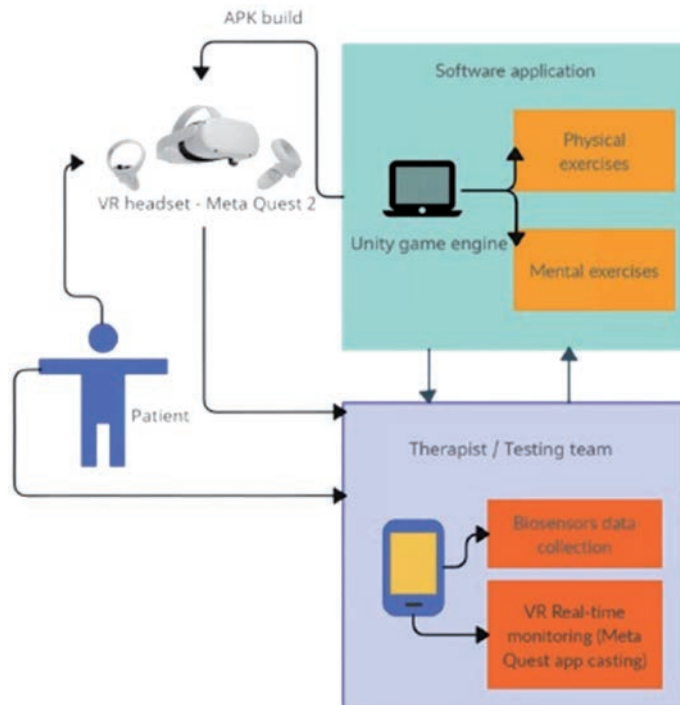


Figure 2.
Schematic diagram of VR system (software and hardware components).

as neurological disorders, post-stroke recovery, and others, to improve motor and cognitive function, as well as mental health treatments [22]. **Table 1** devices are novel devices that enable patients to actively engage with virtual environments to enhance their physical and emotional recovery. The integration of interactive therapies into

Device	Company	Description
Oculus (Quest 2)	Oculus VR	An independent VR without the need for a PC or out of doors sensors. Delivers a very immersive experience that includes 3D and 6-axis (6 DOF) head motion tracking, immoderate resolution, and wireless operation. Virtual rehabilitation applications can gain from their easy-to-use and coffee price features [23, 24].
Oculus (Rift S)	Oculus VR	Requires a PC to operate. An immersive revel in is supplied with 6 DOF head movement monitoring and better face detection without the use of outside sensors. The Oculus Rift S is designed mainly for customers who choose a greater superior VR revel in, with get admission to a huge form of video games and apps, including rehabilitation and therapy [25].
CAREN	Motek Technologies	The Computer Assisted Rehabilitation Environment is a modern-day VR rehabilitation gadget that carries movement and pressure seize era in actual time. It consists of a 6 DOF cellular platform and a 360-diploma theater gadget, offering an immersive revel in for patients. Various neurological and musculoskeletal situations may be evaluated and rehabilitated through the usage of CAREN, which presents managed surroundings for schooling and recovery [26].
BTS Nirvana VR	BTS Bioengineering	It is a VR system for the rehabilitation of patients with neurological disorders. It offers rehabilitation modules aimed at improving motor skills and supporting the patient's overall recovery. By using VR technology, the system allows patients to participate in interactive exercises and engage in activities that stimulate neuroplasticity and motor functions in a controlled and motivating environment [27].
Reh@City	Teresa Paulino, Universidade da Madeira	Enables patients to navigate a virtual urban environment and participate in essential activities of daily living (ADLs), simulating real-life interactions for rehabilitation. This system helps patients improve their mobility skills, independence, and confidence and is used for the recovery of motor and cognitive functions in a context that mirrors everyday life experiences [28].
XR Therapeutic Spaces	XRHealth	It is an XR platform for rehabilitation and therapy that combines VR and AR to create immersive environments tailored to patients' needs. It includes modules for physical rehabilitation treatments, pain management, and cognitive skills improvement, and is used in both hospitals and rehabilitation clinics. The system allows the patient's progress to be monitored and therapy sessions to be adjusted in real-time to maximize the effectiveness of the recovery process [29].
PhysioVR	Virtualis (Perols, France)	A VR solution designed for rehabilitation, offering tailored modules for various conditions. The system is used to improve ADL, balance, motor function, proprioception, cognition, and hemineglect treatment. With an intuitive and interactive design, it supports patients to participate in personalized exercises, accelerating recovery in an engaging and motivating environment [30].
Samsung Gear VR	Samsung Electronics Co., Ltd.	It is a portable VR device that uses a compatible smartphone to provide an affordable and easy-to-use VR experience. Although its functionality is limited compared to other advanced VR systems, Gear VR is a convenient option for exploring VR and interactive experiences [31].

Device	Company	Description
Nintendo Wii variations	Nintendo Co., Ltd.	Offers similar VR experiences using player avatars, which interact with the games through wearable devices and infrared sensors. These systems track body movements for interactive and immersive gameplay. Although not a full VR platform, Nintendo Wii has been a pioneer in integrating physical movement into games, contributing significantly to the popularization of physical interaction technologies [32].
Kinect for Xbox 360/One	Microsoft Corporation	Offers an immersive experience, allowing users to control movements in games using their body, thanks to motion tracking technology and interaction without a physical controller. The system uses advanced cameras and sensors to detect gestures and voice commands and is applicable in both entertainment and medical rehabilitation by promoting natural movements in an interactive virtual environment [33].
Vive Focus 3	HTC Corporation	It is a standalone VR headset that offers 6 DOF tracking and high-resolution optics for an immersive VR experience. It is designed to be used without cables or connections to a PC, making it ideal for mobile applications including rehabilitation. The system allows patients to participate in interactive and personalized sessions, enhancing physical and cognitive recovery in a fully immersive environment [34].
MindMotion™ PRO	MindMaze	The VR device was made for the motive of acute neurorehabilitation. Mass-primarily based totally remedy and 17 designed video games are provided to sufferers improving from top limb hemiparesis with a view to enhance embodiment and regain manage of the top limbs. Through the usage of custom video cameras, optical markers, and inertial devices of measurement, the patented monitoring generation detects and amplifies intentional diffused movements, making them a quintessential part of the game [35].
RAPAEI Smart Glove	Neofect	Provides a modern rehabilitation tool that became created for sufferers who are recuperating from neurological and musculoskeletal injuries, which include stroke. Interactive VR-primarily based totally remedy sporting events may be completed with the assistance of this lightweight, easy-to-put-on glove that makes use of sensors to track hand and finger movements. Through rehabilitation, the tool motivates customers to enhance their motor skills, hand energy and coordination. The synthetic intelligence-primarily based totally machine adjusts remedy obligations to the patient's progress, ensuring personalized and powerful rehabilitation sessions [36].
HoloLens 2	Microsoft Corporation	The superior MR headset can seamlessly integrate digital factors with the bodily world. The immersive and interactive surroundings present a rehabilitation surroundings that permits sufferers to interact in customized healing exercises. The tool functions hand monitoring, eye monitoring and high-decision displays, allowing specific interplay and real-time feedback. With its versatility, it could be used for an extensive variety of rehabilitation applications, from motor characteristic healing to cognitive training, which improves affected person engagement and treatment outcomes [37].

Table 1.
Virtual reality (VR) device used in rehabilitation.

hospitals and rehabilitation centres requires these technologies, which promote a more personalized and effective approach to the healing process.

2.3 Essential elements of virtual reality

VR is an advanced technology that creates interactive environments and experiences using a computerized system. These environments are digitally generated and allow the user to interact with them, creating a sense of deep immersion and physical presence in virtual worlds. VR devices, such as specially designed headsets and goggles, are used to simulate experiences and transport the user into an artificial reality, often different from the real world. By using these technologies, VR can stimulate the user's visual, auditory, and tactile senses, providing a sense of "being present" in the virtual environment, which can be perceived as real, even if it is artificially constructed. Its wide applicability has made VR integrated into numerous domains such as entertainment, education, health, architecture, and many others, revolutionizing the way people interact with technology and the environment [38–41].

Understanding VR technology involves exploring how it creates and manages immersive virtual environments. These environments are built entirely digitally, using special computers and software that allow the generation of realistic or completely imaginary 3D worlds. From detailed representations of the environment to fantasy worlds, VR offers a wide range of possibilities for creating immersive experiences. A key aspect of this technology is graphical representation, which focuses on details such as lighting and textures, which are fundamental to creating a plausible and realistic virtual environment. Visual details help amplify the sense of presence in the virtual world, thus contributing to an immersive and authentic experience for the user [42–44].

Immersion in VR is the sensation of being physically present in a fully digital environment, achieved by creating holographic experiences that make the user forget about the real environment during interaction. An essential element of immersion is the user's interaction with devices that monitor body movements and translate them into the virtual environment. These devices, such as VR goggles or specialized gloves, allow natural and fluid interaction with the holographic environment, enhancing the feeling of physical presence and intensifying immersion. Thus, the user feels as if they are part of the virtual world, not just an observer [45–47]. Real-time interaction is a fundamental aspect of VR, allowing the user to interact directly and immediately with the virtual environment. This is achieved by manipulating objects, communicating with characters in the digital world, and actively influencing the environment. Two-way interactions are essential to create an authentic and immersive experience. In addition, to enhance the immersion and reality of these interactions, many VR devices include haptic feedback, which provides tactile sensations through vibrations, simulating touching and manipulating objects. These technologies contribute to a more natural and interactive user experience, more closely approximating physical reality [48–49].

The simulation and representation of 3D objects are essential in creating virtual environments, using advanced 3D modeling techniques to generate objects, characters, and landscapes that can range from realistic to fantastic. These objects are integrated into a digital environment that respects the principles of physics, such as gravity, collisions, or fluid interactions, to provide a more authentic and immersive

experience. Physical simulation plays a crucial role in the realism of VR environments, as it helps to create an accurate perception of the behavior of objects in the virtual world, thus contributing to the immersion and interaction of users with these worlds (**Figure 3**) [50, 51].

Sensors and motion tracking are crucial for interpreting and replicating user movements in a virtual environment. VR devices use a combination of technologies, including tracking cameras, gyroscopes, and accelerometer sensors, to recognize body gestures and movements. The use of these technologies allows users to control the holographic environment with the help of their hands or bodies, resulting in a more natural and intuitive interaction. The use of motion tracking technologies is crucial to ensuring an immersive and realistic experience and creating a sense of presence in the virtual world [52–54].

The future of virtual reality in rehabilitation engineering is being driven by VR's therapeutic benefits, technology advancements, and interdisciplinary research. The use of wearable sensors and biofeedback devices will make it possible for VR systems to regulate therapy intensity, duration, and focus according to physiological responses such as heart rate, muscle activity, and neural feedback. VR's ability to stimulate multiple senses simultaneously allows it to stimulate neural pathways and help with recovery from strokes, traumatic brain injuries, and neurodegenerative conditions.

3. Using artificial intelligence (AI) in assistive devices engineering

It is truly remarkable that assistive technology is at the forefront of technological development. Many technologies have made their way to people with disabilities long before they became mainstream, such as audiobooks and text-to-speech software [54]. Other examples include natural language processing, word prediction software, and personal assistants. However, the reverse is also true: as the availability of standard technologies and universal design rules increases, these technologies are

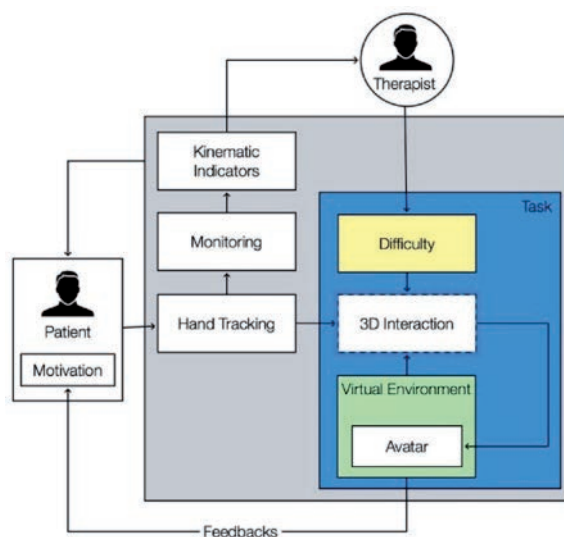


Figure 3.
Schematic diagram of VR in medical rehabilitation application.

becoming essential for people with disabilities and others to participate in community life and impact those around them. Assistive devices such as prostheses, orthotics, hearing aids, and walkers have long played a vital role in improving the quality of life for people with disabilities [55]. However, traditional rehabilitation methods are often based on trial and error, which can be time-consuming and difficult. Artificial intelligence provides solutions by leveraging evidence-based insights to improve device effectiveness and patient management [56].

Assistive technologies are used in many areas of personal care, not just mental health. They are used for dementia, autism, spinal cord/knee injuries, quadriplegia, tetraplegia, exoskeletons, diabetes (in the form of orthopedic shoes), stroke, mobility, cognition, vision, nutrition, and hearing functions as well as personal emergency response systems, educational access software, computer access, smart home technology for the elderly, walkers, elder care, and many more. **Figure 2** shows the various application areas of assistive technologies [57]. People with progressive functional loss can also benefit from assistive devices. These include orthopedic support, vehicle modifications, entertainment devices, environmental control, communication aids, service animals, and educational assistance. Artificial intelligence and machine learning methods can enable more accurate diagnosis by identifying disabilities and facilitating the effective use of assistive devices [58]. Related applications and smartphones make it easier and more convenient for ordinary people to use assistive devices (**Figure 4**).

3.1 Applications of AI in mobility assistive devices: Exoskeletons

Artificial Intelligence (AI) is a notable change in the design, functionality, and usability of exoskeletons. The integration of AI has resulted in exoskeletons becoming smarter, more adaptive, and capable of significantly improving mobility, strength, and rehabilitation outcomes. Exoskeletons are wearable robotic systems that provide mechanical support and assistance to individuals with physical impairments, aiding in mobility, rehabilitation, and performance enhancement. AI-driven advancements make these devices smarter and more effective by integrating real-time adaptability and user-centric customization. The essential capacities of individualities can be enhanced to a significantly lesser extent by exercising an external frame appertained to as an exoskeleton. It also aids in mending damage sustained. A lower branch exoskeleton assists individuals who struggle to conduct their daily tasks. They grease walking and performing with the help of electric motors. The upper branch exoskeleton is a device that can be moved and attached to the arm. Commands to operate the device are handed by the stoner [59]. The category of lively exoskeletons is decided through their presence of motors, at the same time as unresistant bones are diagnosed through their absence of motors. The chance of musculoskeletal accidents may be minimized while lifting heavy details with a powered or lively exoskeleton. The use of passive exoskeletons is meant to help objects, offer ergonomic help, and help with accidents. The layout of quasi-passive exoskeletons is to help masses at the same time as strolling and consists of a knee variable mute, alongside hip and ankle springs [60].

AI in lower limb exoskeleton rehabilitation improves mobility and recovery, allowing for adaptive, personalized treatment. By analyzing data in real time, AI optimizes the exoskeleton's movements to match the user's intent, adapts rehabilitation plans and provides continuous feedback. It supports motor relearning, improves safety, and accelerates recovery by predicting progress and adjusting support levels accordingly (**Figure 5**). This integration helps people with mobility impairments regain their movement more efficiently and effectively [61].

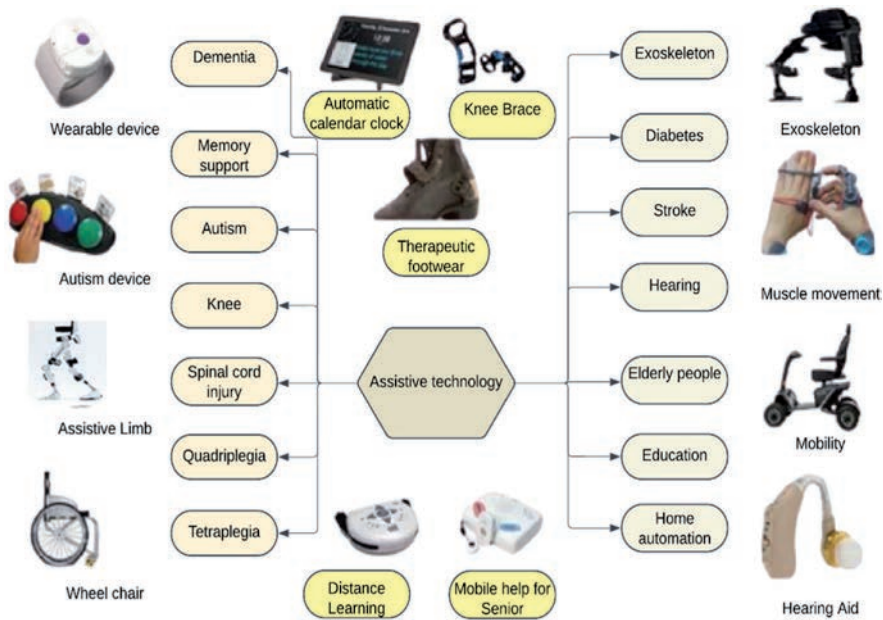


Figure 4.
Assistive technology application fields.

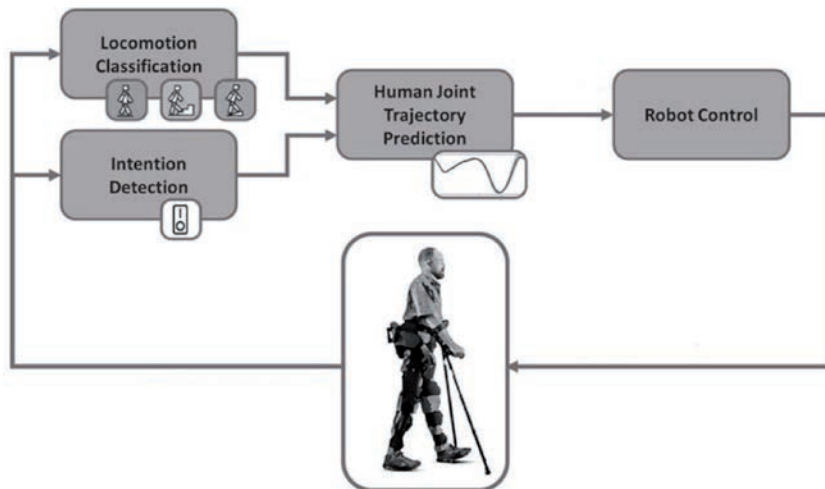


Figure 5.
Using AI in lower limb exoskeleton rehabilitation.

AI features in exoskeleton devices are:

- *Adaptive control systems:* AI methods sensor records along with motion, muscle activity, and stress to make real-time modifications to exoskeleton movements. This lets in for adaptive gait styles that assist customers to stroll naturally, even in dynamic environments.

- *Personalized machine learning*: AI continuously learns from the user's biomechanics and behavior, fine-tuning the exoskeleton to meet individual needs. Over time, it enhances key aspects like speed, balance, and endurance.
- *Rehabilitation assistance*: AI-powered exoskeletons aid physiotherapy *via* way of means of guiding unique movements, making sure right posture, and handing over real-time comments to therapists.
- *Environmental awareness*: AI-pushed sensors locate obstacles, terrain variations, and different environmental factors. The gadget adjusts therefore to one-of-a-kind surfaces, which include stairs, slopes, and choppy ground, to enhance safety.
- *Brain-computer interfaces (BCIs)*: Advanced AI translates neural alerts from BCIs, permitting customers to manipulate the exoskeleton *via* thought. This is specifically useful for people with intense mobility impairments, together with spinal twine injuries.
- *Optimized energy efficiency*: AI complements electricity control with the aid of using predicting movement styles and directing electricity in which it is far wished most, maximizing efficiency [62].

3.2 Application of cognitive assistive devices

Cognitive assistive devices are advanced technologies designed to aid individuals with cognitive impairments, such as memory loss, attention deficits, or executive function challenges. These devices utilize innovative technologies, including artificial intelligence (AI), to help users manage daily activities, enhance independence, and improve their overall quality of life [63]. AI-powered algorithms enable these devices to anticipate user needs and provide personalized support in conjunction with advanced sensors. For instance, portable electroencephalograms (EEGs) monitor brain activity, while biometric sensors track stress levels, attention, and heart rate. Ongoing research also explores neural implants—systems that stimulate specific brain regions to enhance cognitive functions.

Application of cognitive assistive devices:

Medicine and rehabilitation: support for patients with neurodegenerative diseases (e.g. Alzheimer's and Parkinson's), cognitive rehabilitation after strokes or head injuries or devices for managing anxiety, depression, or ADHD.

Education: personalized learning systems that analyze students' cognitive styles or apps that support people with learning disabilities (e.g. dyslexia).

Support in daily activities: electronic organizers that provide reminders or help with planning activities.

Social integration: real-time translation systems for sign language or assisted speech. Technologies that help people with autism spectrum disorders interpret facial expressions and tone of voice [64].

The future of artificial intelligence (AI) is poised to revolutionize assistive devices engineering, making them more adaptive, intuitive, and accessible. With advancements in AI technologies and their integration into assistive devices, the future holds transformative possibilities for individuals with physical, cognitive, and sensory impairments. AI systems will continuously refine their responses based on user interactions and real-time data, ensuring optimal support [65].

4. Brain computer interface (BCI) applications in assistive devices

The Brain-Computer Interface (BCI) is a method by which the brain can communicate directly with an external device, bypassing traditional neuromuscular pathways. BCIs are used to restore, improve, or supplement human cognitive and sensory-motor functions. The brain activity is captured by BCIs through sensors or electrodes. The common technique is:

- EEG (electroencephalography): measures electrical activity on the scalp.
- fMRI (functional magnetic resonance imaging): detects changes in blood flow in the brain.
- ECoG (electrocorticography): measures activity from the surface of the brain.
- MEG (magnetoencephalography): measures magnetic fields from neural activity.

Raw brain signals are processed to extract meaningful information. This includes preprocessing, which involves filtering out noise and artifacts (e.g. from muscle movements or eye blinks). The next step is featuring extraction and identifying patterns in the brain signals related to specific intentions or states. Finally, classification uses algorithms such as machine learning to map extracted features to commands or actions.

Assistive devices that empower individuals with disabilities to interact with their surroundings, communicate, and regain functional independence are developed using BCIs [66].

Examples of brain-computer interface (BCI) applications in assistive devices:

- *Communication devices*—BCIs help individuals with conditions like ALS (Amyotrophic Lateral Sclerosis) or locked-in syndrome communicate effectively;
- *Mobility assistance*—BCIs facilitate mobility for individuals with severe physical impairments: wheelchair control, prosthetic limbs, exoskeletons;
- *Environmental control*—BCIs empower users to interact with their surroundings: smart home integration: to control over devices like lights, thermostats, TVs, and doors through neural commands, enhancing independence for users with mobility impairments or assistive robots;
- *Visual and sensory aids*: to improve sensory capabilities for individuals with sensory deficits (**Figure 6**).
- *Rehabilitation devices*: BCIs are utilized in neurorehabilitation to useful resource recuperation from accidents like strokes. BCIs blended with digital reality (VR), or robot structures inspire motor relearning with the aid of offering remarks as customers try to pass paralyzed limbs. Cognitive schooling involves the usage of BCIs display mind hobby at some stage in rehabilitation sporting events and adapt obligations to enhance cognitive and motor functions (**Figure 7**) [68].

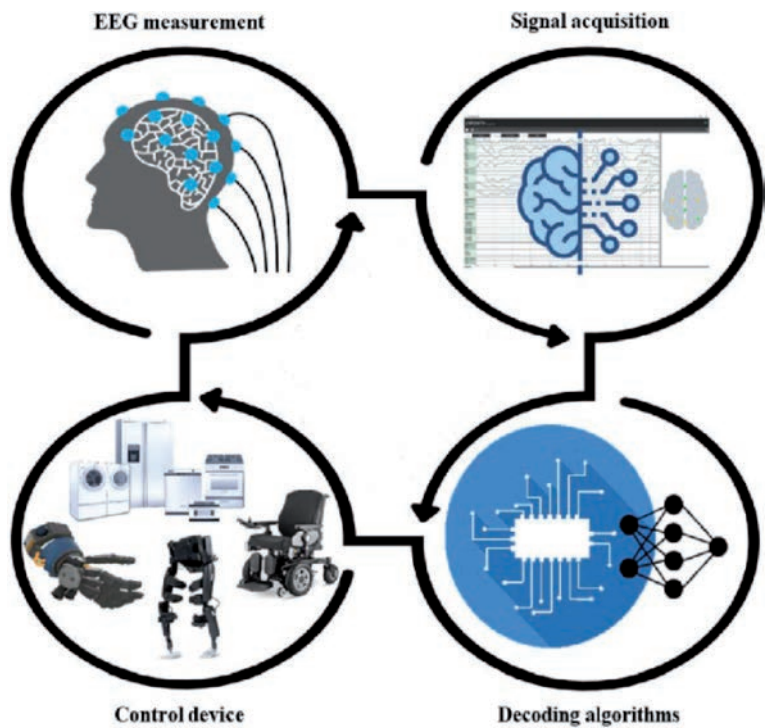


Figure 6.
An overview of a typical BCI system [67].

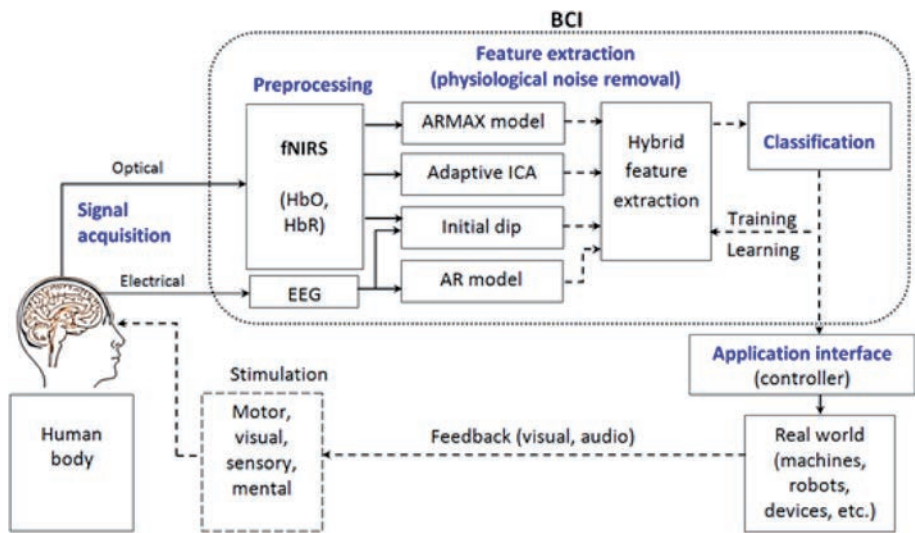


Figure 7.
BCI diagram—relationships between the component blocks of the system.

The destiny of BCI includes growing extra superior algorithms for processing EEG, MEG, or fMRI indicators to boom the accuracy of decoding mind indicators, decreasing noise withinside the captured indicators and growing the robustness of

the gadgets in actual conditions. Also, the combination of device getting to know and synthetic intelligence (AI) strategies for extra unique evaluation and quicker predictions.

5. Ethical considerations regarding assistive devices in rehabilitation engineering

Assistive gadgets utilized in rehabilitation engineering provide sizeable advantages to human beings with disabilities; however, additionally they also enhance numerous essential moral considerations. These challenge problems are associated with autonomy, privacy, equity, safety, and the effect of the great existence of users [69].

Some aspects that require attention in the development of assistive device systems:

- *Respecting personal choices*—it is essential that users have the freedom to decide on their device usage and settings, without external pressure;
- *Minimizing dependency*—technologies should be designed to enhance user autonomy, not to create excessive dependency on the device or service provider;
- *Information security*—devices collect sensitive personal and medical data; it is crucial that this is protected against unauthorized access or misuse;
- *Transparency of data use*—users should be informed about what data is being collected, how it is stored, and how it will be used;
- *Surveillance prevention*—assistive systems that monitor users (e.g., in home rehabilitation) can violate the right to privacy if not used appropriately;
- *stigma*—using assistive devices can attract unwanted attention or social labels, which can negatively affect the user's self-esteem;
- *Loss of confidence in one's own abilities*—excessive support provided by technology can reduce the user's motivation to improve their natural abilities;
- *Acceptance of technology*—some people may experience emotional or psychological resistance to using devices, considering them invasive or inconvenient;
- *Artificial intelligence in devices*—AI algorithms that make decisions on behalf of the user must be programmed to respect their preferences and needs.
- *Risk of manipulation*—devices that learn from the user's behavior could influence their choices in an unethical way [70, 71].

6. Conclusions

The integration of emerging technologies into assistive devices is revolutionizing the field of rehabilitation engineering, offering unprecedented opportunities

to enhance the lives of individuals with disabilities. Advancements in artificial intelligence (AI), virtual reality (VR), robotics, and brain computer interface (BCI) are synergistically transforming assistive devices into smarter, more adaptive, and user-centric solutions. These technologies enable real-time personalization, seamless interaction, and enhanced functionality. The fusion of emerging technologies with assistive devices marks a change in thinking in rehabilitation engineering. By addressing the challenges and capitalizing on technological advancements, the field can continue to innovate and create a more inclusive, equitable, and empowered society for individuals with disabilities.

Conflict of interest

The authors declare no conflict of interest.

Author details

Călin Corciovă*, Robert Fuior, Ilie Onu and Cătălina Luca
Medical Bioengineering Faculty, “Grigore T. Popa” University of Medicine and Pharmacy of Iasi, Romania

*Address all correspondence to: calin.corciova@bioinginerie.ro

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Perspective Chapter: Semi-Rigid Cervical Orthosis as an Ergonomic Solution to the Detrimental Effects of Head-Loading

Chanelle Ribeiro-Wagener, Terry Jeremy Ellapen and Yvonne Paul

Abstract

Head-loading is a common practice among rural African communities, where women and girls transport heavy loads, such as water and firewood, using their heads. This tradition, although a culturally significant practice, exposes individuals to long-term postural misalignment leading to neuro-musculoskeletal pathology, particularly in the cervical and lumbar vertebrae. The adverse effects include vertebral pain, intervertebral disc compression, and an increased risk of cervical spondylosis, spondylolisthesis, excessive lumbar lordosis, and anterior pelvic tilt. This perspective chapter explores the application of a semi-rigid cervical orthosis as an ergonomic solution to reduce the detrimental effects of head-loading. By redistributing cranial load and stabilising cervical posture, the orthosis aims to reduce strain on the cervical vertebrae, improving muscle function and overall body posture. This chapter summarises current research on important factors such as muscle activity, body measurements, body awareness, and lung function in young girls who carry loads on their heads daily. The health implications of head-loading on posture and musculoskeletal well-being are presented through the examination of findings from the theoretical and applied scientific works. This analysis highlights the relevance of these studies for populations where head-loading is prevalent and explores evidence-based insights to provide an ergonomic medical orthotic solution. Overall, this chapter emphasises the importance of understanding these health dynamics to guide future research and potential interventions, particularly in impoverished communities.

Keywords: cervical orthosis, head-loading, musculoskeletal disorders, neuromusculoskeletal, postural deviations

1. Introduction

Head-loading is the practice of carrying external heavy loads on the porter's head, which remains a prevalent mode of transport in rural communities across

Africa and Asia [1–5]. In Africa, this culturally significant activity has been practised for centuries, particularly by women and young girls, who are often tasked with the responsibility of transporting essential resources such as water, firewood, and food over considerable distances [1, 2]. Head-loading is commonly practised in geographical regions where communities have limited transportation infrastructure (no motorised vehicles and poorly maintained roads or footpaths) [1, 2] and is associated with notable health risks, particularly neuro-musculoskeletal pathology concerning the cervical and lumbar vertebrae alignments [6–9]. There are two predominant methods of carrying external head-loads, namely the Asian method and the African method. Both of these methods of head-loading have gained considerable research attention [3–5, 10–14].

Head-loading is a deeply ingrained African cultural practice, with its significance linked to specific gender roles. African females (young and old) are principally tasked with head-loading in association with economic, historical, and pragmatic reasons. Head-loading, also known as cranial loading, is seen as an efficient method of transporting essential items such as firewood, food, and water. Further, the practice of head-loading lies within the ambit of the traditional gender work roles, whereby females' responsibilities are focused on domestic tasks and resource management [1, 2]. Most traditional African communities assign females the primary responsibilities for domestic tasks and resource gathering. This distribution of labour aligns with broader analyses of shifting gender roles in African households [15]. In many settings, these roles concentrate on domestic transport tasks—such as water and wood carriage—among women and girls, reinforcing the cultural embedding of head-loading and its day-to-day necessity [1, 2]. Domestic tasks include cleaning and sweeping the house, completing the laundry, cooking meals, and chaperoning the children and the elderly within the family and community [1, 2]. Head-loading can additionally be viewed as an extension of the role of resource management as well as participating in community activities. Under certain conditions, head-loading portage may serve as a means of income generation for the family. Rural African females head-load their produce to market with the intention of selling it or provide the service of transporting goods for other community members in exchange for money or other resources. The practice of head-loading is also seen as an exercise of community cohesion and collaboration among females working together to share the burden of carrying large quantities of resources. Older females often teach younger females how to carry head-loads efficiently sometimes described as building up body capital [1]. Girls as young as 5 years of age start to carry head-loads of up to 3 kg. These head-load masses progressively increase, sometimes to as much as 35 kg, during their adolescence and adulthood. A study by Ellapen and colleagues reported an average head-load mass of 20.7 kg in a cohort of rural adolescent females (12–15 years), which equated to 50.2% of their averaged body mass (41.2 kg) [7]. Geere and colleagues reported that a cohort of African female adolescents head-loaded an average load mass of 58.3% (28.9 kg) of their respective body weight (49.5 kg) [2]. A more extreme finding was published in a study on adult females by Lloyd and colleagues, who documented head-load masses comparable to 70% of their cohort's average body mass [11]. In many rural African communities, as soon as an adolescent female reaches the age of 15 years, she is expected to carry adult head-loads of a minimum mass of 25 kg while walking distances from 2 to 10 km every day [1, 2, 9]. Building up body capital is a cultural phenomenon practised by these community members in order to progressively increase the porter's head-load mass by increasing muscle strength, endurance, and cardiorespiratory endurance as the child grows [1].



Figure 1.

A conceptual illustration of a young woman carrying a woven basket using a head strap on hilly terrain. This AI-generated image was created to depict Asian traditional head-loading practices in rural communities and does not portray a real individual.

Although this chapter exclusively focuses on the optimistic application of a cervical orthosis for African head-loading porters, the authors make reference to another popular method of head-loading that being the Asian Nepalese method. The insights offered in this chapter can be applied to either head-loading method (**Figure 1**) [3–5].

1.1 Asian head-loading method

- Namlo–Doko (Nepalese) method. Nepalese porters use a head strap (namlo) attached to a bamboo basket (doko). The namlo transmits load through the forehead and cervical region to the axial skeleton, reducing reliance on the shoulder girdle, while the doko contains the payload [3–5]. During upright carriage, the compressive line of action follows the spine from cervical to sacral segments, consistent with closed-kinetic-chain load transfer [16]. Regarding health risk, imaging in head-loading labourers shows cervical disc height loss/degenerative change consistent with spondylosis [8], yet a Nepalese radiographic study reported lower prevalence of cervical spondylosis in porters than non-porters [17]; thus, the long-term effect of tumpline carriage remains uncertain and warrants prospective study. Nepalese porters routinely carry very heavy relative loads efficiently in steep terrain, aided by the specialised technique [3, 5]. Although head-supported carriage can display energy-saving mechanics [18], the idea of a universal “free ride” is contested in African comparisons of head- versus back-loading [11].

1.2 African head-loading method

- In Africa, head-loading involves balancing heavy items like water containers, firewood, and baskets directly on the porter’s head without additional straps.

This traditional method relies on balance, posture, and experience for efficient head-load portage. African porters commonly use a soft cloth twisted into a circular ring atop the head to stabilise and cushion the load [1]. Energy-expenditure investigations have examined the metabolic cost of this method [10–14, 19, 20]; however, these seminal investigations did not reach a consensus on the energy-efficiency of head-loading as a mode of load carriage [10–14]. Early work advocated that head-supported carriage can be efficient under specific conditions [12, 18]. For example, Maloiy and colleagues reported that some African females could carry head-loads around 20% of body mass with little or no extra metabolic cost compared with smaller loads [12]. Charteris referred to this observation as the “free-ride” hypothesis [13]. Beyond such low relative loads, subsequent experiments showed that metabolic cost rises approximately with added mass and speed, challenging the notion of a universal advantage [10, 11, 14]. These proposals have also been criticised for small samples and for the confounding effect of extensive lifetime practice among habitual head-loaders [1, 10, 11]. Other researchers recommended backpack loading as a more energy-conservative method of load transportation than African head-loading in some tasks [19, 20]. Overall, the question of whether African head-loading is energy-conservative depends on load magnitude, terrain, walking speed, and carrier experience, and remains a topic for prospective metabolic investigation (**Figure 2**) [10–12, 14].

The biomechanical challenges of head-loading arise from the continuous strain it places on the axial skeleton’s musculoskeletal system, especially the cervical and lumbar vertebrae, shoulders, and knees. The practice of head-loading adheres to the closed kinetic chain activity concept. The hallmark characteristic of a closed



Figure 2.
Africa women carry baskets on their heads as a method of transporting goods, laundry, and even water.

kinetic chain activity is where the hand or foot is fixed in place and remains in contact with a stable surface during movement, such as the ground or the base of a machine. Movement at one joint in the closed kinetic chain will produce movement at other joints in the chain. Postural deviation in the cervical vertebrae will misalign the thoracic and lumbar vertebrae, pelvis, knees, and feet. This is known as serial distortion of the kinetic chain [16]. When loads are placed on the head, the cervical vertebrae, neck muscles, and shoulder girdle bear the weight, often misaligning from their anatomically normal posture, producing musculoskeletal discomfort, pain, and fatigue and even long-term conditions such as cervical spondylosis [6–9, 21]. Regularly carrying weight on the head has been linked to neck and shoulder pain, along with the misalignment of the vertebrae, due to constant pressure on the cervical spine [1, 22]. Ellapen and colleagues graphically illustrated these postural changes induced by head-loading (**Figure 3**) [7]. Literature suggests that this practice may also compromise proprioceptive abilities and balance, as the body must continually adjust to maintain stability under load [9]. Ellapen and colleagues reported that when females head-loaded, they experienced increased cervical and lumbar lordosis [7]. Further, the females' cervical flexors and extensors significantly increased their muscle activity to stabilise the external load and maintain their posture and simultaneously balance the head-load as illustrated in **Figure 3** [23]. **Figure 3** illustrates the greater neck flexor and extensor electromyographical activity when females are head-loaded, as documented by Ellapen et al. and Kurten et al. [7, 23]. Ellapen and colleagues' findings supported the seminal work of Echarri and Forriol, who also indicated that head-loading produces degenerative cervical changes consistent with spondylosis [6, 9, 21]. Anterior spondylolisthesis refers to anterior sliding of a superior vertebra over an inferior vertebra; while a recognised pathology,

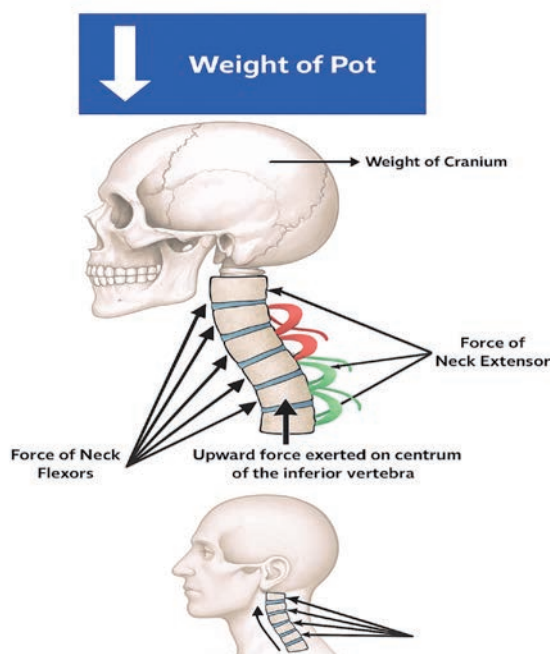


Figure 3.
 Graphic illustration of increased cervical flexor and extensor activity to stabilise the head-load [6].

the cited studies chiefly report curvature and disc/degenerative changes rather than definitive anterior slip [6, 9, 21].

Researchers have commented that the traditional method of head-loading in Africa will never be terminated despite the harm it causes. Head-loading remains one of the only method of resource transportation readily available to many rural African communities and it bares cultural and historical significance [1, 2]. Therefore, rather than eliminating the practice, medical practitioners and healthcare rehabilitation scientists should prioritise developing ergonomic strategies to alleviate postural misalignment during head-loading. In an attempt to confront these challenges, this chapter reviews the potential benefits of a semi-rigid cervical orthosis as an ergonomic intervention for the vertebral misalignment and ill health effects associated with head-loading. This device is intended to stabilise the cervical vertebrae by redistributing cranial loads, thereby reducing strain on the cervical vertebrae, intervertebral discs, ligaments, and muscles, and overall improving postural alignment [7, 9, 16, 23]. The intervention has a dual purpose: alleviating immediate discomfort while potentially preventing the long-term progression of musculoskeletal pathology in populations where head-loading is a common practice [6, 8, 21].

The chapter provides an overview of head-loading practices and examines their health implications. It introduces the semi-rigid cervical orthosis as a possible ergonomic solution to health complications, and the authors further encourage electromyographical, kinanthropometrical, and goniometrical assessments to evaluate its effectiveness. By synthesising insights from existing research, the chapter aims to contribute to the growing body of knowledge. It seeks to provide a practical and financially inexpensive strategy for improving health outcomes in impoverished communities, applicable in both rural and urban contexts [1, 2].

2. Methodology

This perspective chapter synthesises practitioner experience, contextual knowledge from African head-loading communities, and targeted concept-checking against authoritative sources to develop an ergonomically grounded argument rather than to report aggregate study findings. The authors (CRW, TJE) first established the scope (African head-loading practices, neuro-musculoskeletal mechanisms, and pragmatic mitigation in low-resource settings) and *a priori* propositions (e.g., load paths, posture and muscle-activation demands, feasibility constraints). We then undertook focused horizon-scanning to verify terminology, typical exposure ranges, and feasibility considerations using key, well-known references only to triangulate concepts, not to perform an exhaustive review. Evidence and practice insights were organised into domains (exposure/technique, biomechanics, symptoms/function, and ergonomic options), and points of uncertainty were explicitly identified. Illustrations and figures are original or reproduced with permission. This approach privileges clarity of mechanism, clinical plausibility, and implement ability; it does not claim systematic coverage of the literature and avoids quantitative synthesis by design.

3. Health impacts of head-loading

Head-loading imposes high compressive and shear forces on the cervical spine, with radiographic and clinical evidence of curvature change, disc height loss, and

degenerative features compatible with cervical spondylosis [6, 8, 21]. In adolescents, habitual head-loading is linked to measurable sagittal misalignment of the head-neck-trunk, indicating early structural adaptation [7, 24]. During loaded carriage, cervical flexor and extensor activation rises and head-neck posture shifts—responses that stabilise the load yet increase cumulative tissue stress [23]. At the symptomatic level, women who frequently carry heavy head-loads report neck/back pain and activity limitation, consistent with musculoskeletal burden described in regional reviews [1, 22]. Emerging youth data also show proprioceptive and broader neuromusculoskeletal effects, suggesting potential balance implications with repeated exposure [9, 25].

3.1 Cervical vertebral misalignment

One of the most immediate effects of head-loading is increased compressive and shear demand on the cervical motion segments and their intervertebral discs, which can precipitate vertebral malalignment and disc height loss [6, 8, 21]. In adolescents, Ellapen et al. reported load-related deviations in sagittal alignment—including forward head posture—with accompanying changes along the head-neck-trunk chain [7]. These observations are consistent with radiographic and clinical reports of degenerative change compatible with cervical spondylosis in head-loading populations [6, 8, 21].

Subsequent investigations in youth and young women also document altered cervical posture during loaded carriage: Kurten et al. found changes in head-neck alignment with increased cervical flexor and extensor activation under load [23], and Ntjana et al. observed mass-dependent postural adjustments in pubescent girls [24]. Notably, the direction of cranial translation is not uniform across cohorts—some report forward head posture [7], whereas others describe posterior translation or different compensatory patterns [23, 24], underscoring the need for further work to characterise segmental kinematics under varying loads and ages.

These alignment changes shift load sharing to cervical stabilisers, with compensatory over-activation of muscles such as the cervical extensors and upper trapezius evident on surface EMG during head-loading [23]. Over time, cumulative tissue loading is associated with neck pain and activity limitation in women who frequently carry heavy loads [1, 22], and with broader community burdens linked to domestic water carriage (**Figure 4**) [2, 26].

3.2 Lumbar vertebral alignment

Head-loading affects not only the cervical vertebrae but also the lumbar vertebrae as part of a serial distortion in the closed kinetic chain system [16]. To counterbalance the cranial load, individuals often exhibit compensatory postural adjustments that excessively hyper-extend lumbar vertebrae and anteriorly rotate the pelvis [7, 16, 24]. Anterior rotation of the pelvis is commonly known as the short arc of pelvis-on-femur flexion [16]. The short arc pelvic movement involves rotating the pelvis forward through a smaller arc around the stable femur [16]. This short arc pelvic movement can lead to potential muscle imbalances and compensatory movements in other areas of the body [16]. These adjustments frequently manifest as exaggerated lumbar lordosis, placing increased mechanical stress on the lumbar vertebrae [14, 16, 24]. The misaligned posture reduces the normal weight-bearing curves of the vertebrae from front to back [16]. Over time, these postural changes predispose individuals to chronic lower back pain, degenerative spinal changes, and decreased lumbar flexibility, all of which can compromise overall spinal health (**Figure 5**) [1, 22].

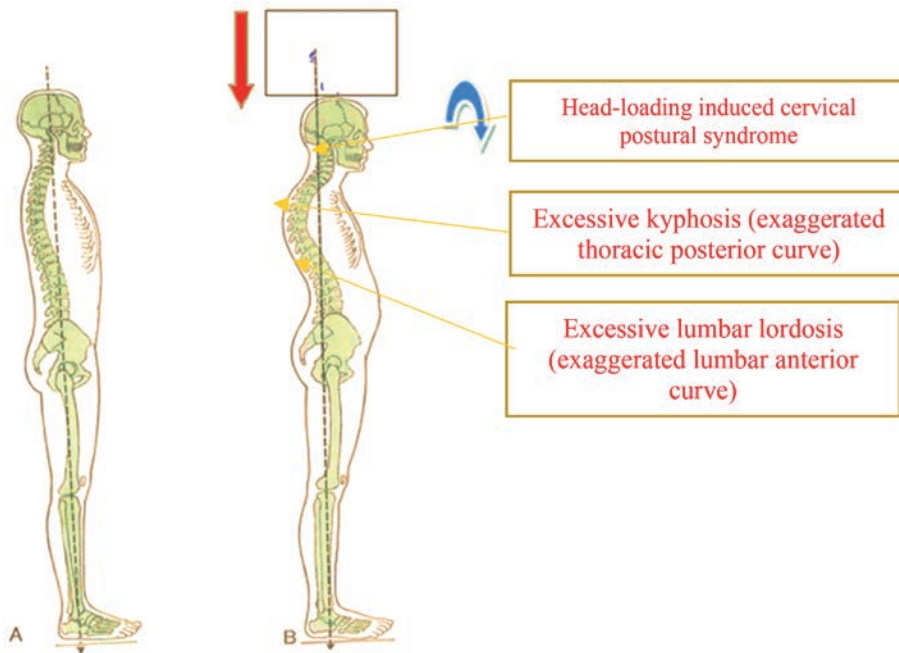


Figure 4.
Effects of head-loading on the vertebral column [6].

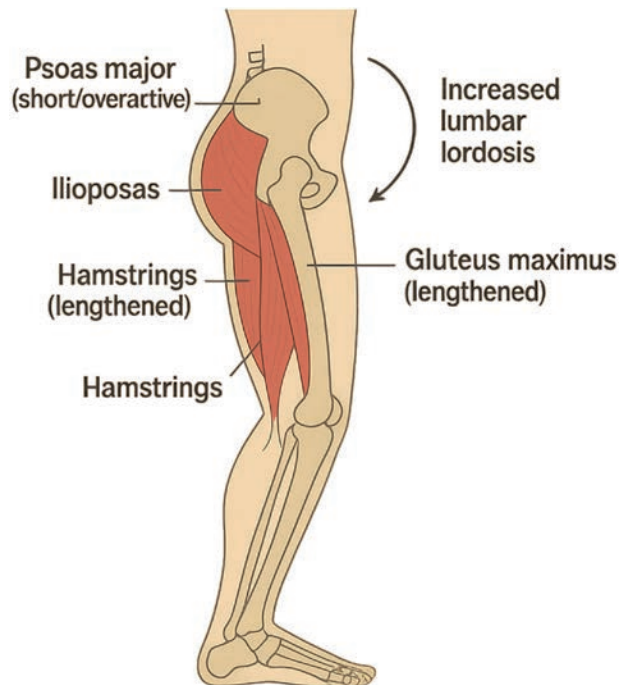


Figure 5.
Side-view of pelvis, femur, and lumbar spine with an arrow showing anterior pelvic tilt; iliopsoas highlighted anteriorly (short/overactive) and gluteus maximus/hamstrings posteriorly (lengthened/underactive); lumbar curve accentuated. Illustration © CRW & TJE (conceptual basis [16]; posture/context [1, 7]).

3.3 Genu recurvatum

The mechanical demands of head-loading also extend to the lower extremities, particularly at the knees. Genu recurvatum, or hyperextension of the knees, is commonly observed among habitual head-loaders [1, 10, 16]. This condition arises as the body compensates for the head-load weight by anteriorly rotating the pelvis, which inevitably hyperextends the knees to maintain balance [7, 16]. Anterior pelvic tilt produces hip flexor (iliopsoas and rectus femoris) contractures [16]. When porters head-load, they are in a closed kinetic chain system, which changes the movement of the muscle contraction [16]. In closed kinetic chain movements, the part of the rectus femoris muscle that connects to the tibial tuberosity moves up toward where it originates at the anterior inferior iliac spine. This muscle action pulls the patella and tibial tuberosity upwards, producing hyperextension of the knees [16]. Over time, this adaptation leads to ligamentous laxity and altered joint mechanics, which compromises knee stability [1, 16, 22]. These changes increase the risk of injuries and long-term degenerative conditions, especially for individuals who begin head-loading at an early age [1, 22]. The potential tibiofemoral health risks include anterior cruciate ligament rupture, patella maltracking, patellofemoral pain syndrome, and osteoarthritis (**Figure 6**) [1, 16, 22].

3.4 Pes planus

The continuous strain of carrying heavy loads also impacts the feet, often resulting in pes planus (flat feet). Continuous stress weakens the supporting structures of the feet, reducing their capacity to absorb shock and maintain stability [22]. Pes planus impairs gait efficiency and contributes to additional stress on the lower limbs and vertebral anatomy, exacerbating musculoskeletal strain. This highlights the cascading biomechanical effects of head-loading on the entire body [1]. Pes planus can also be viewed as a balancing strategy because it increases the base of support. A flatter foot has more stability [16, 22]. Pes planus influences foot kinematics, kinetics, muscle

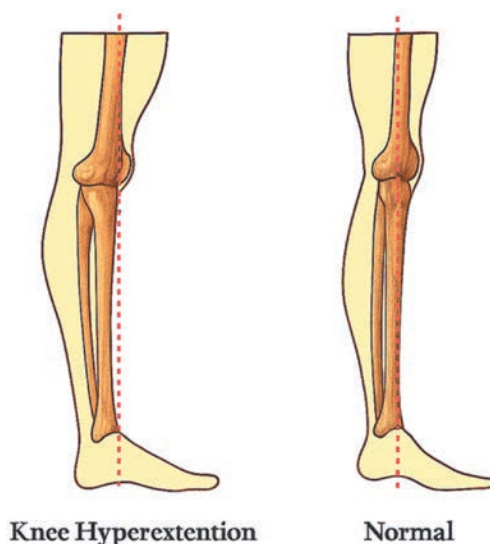


Figure 6.
Knee hyperextension vs. normal knee alignment.

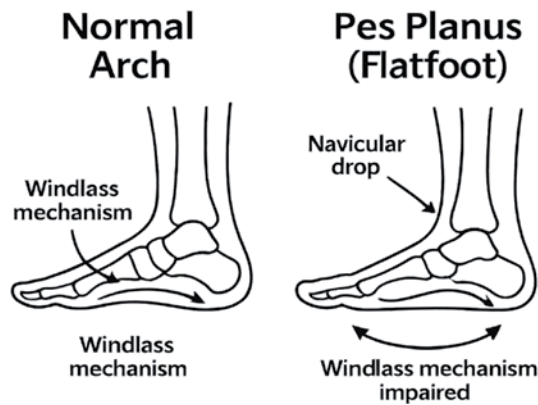


Figure 7.
Normal vs. pes planus (windlass mechanism).

activity, ligamentous stability, and gait patterns. Flat feet change foot kinematics by increasing rearfoot eversion—the calcaneus tilts outward into valgus (not inwards). This increased calcaneal eversion is accompanied by greater pronation (a coupled motion of eversion, forefoot abduction, and dorsiflexion) during walking. The forefoot displays greater plantar-flexion and abduction. These biomechanical changes may influence balance. Flat feet change foot kinetics through the drop of the medial arch, especially the navicular bone, which affects how the foot spreads weight [16]. Individuals with pes planus may experience challenges with foot weight distribution, precipitating greater pressure on the lateral side of the foot and ankle [16]. During late stance, dorsiflexion of the hallux tensions the plantar fascia as it winds around the metatarsal heads (the “windlass” effect), which raises the medial arch, shortens the foot, and stiffens the midfoot into a rigid lever for propulsion; in pes planus—especially under head-loading—the plantar fascia is relatively pre-lengthened and the windlass engages less effectively, leading to prolonged pronation and a less efficient push-off [16]. Flat feet lead to muscle asymmetry, especially of the posterior tibial tendon, which is the primary stabiliser of the medial arch. In addition, the ligaments supporting the medial arch (spring ligament) become lax and cannot effectively perform their function [16]. Flat feet change foot biomechanics by increasing pronation, changing foot strike patterns, and causing difficulty with single-leg balance in the stance phase. Flat feet are also associated with other foot and ankle pathologies, such as Achilles tendonitis, plantar fasciitis, and musculoskeletal pain in the lower leg, knee, hip, and/or back (**Figure 7**) [22].

3.5 Proprioception and balance in head-loading

Proprioception, the body’s ability to sense its position and movement, is critical for maintaining balance and coordination [16]. Head-loading impairs proprioceptive function, particularly in the medial-lateral plane, as the body constantly adjusts to stabilise the cranial load. The sustained compressive forces on cervical proprioceptors diminish their sensitivity, reducing the body’s capacity to respond effectively to postural changes [9, 27].

Additionally, proprioceptive sensors in the lower limbs, particularly in the knees and feet, become overstimulated due to repetitive loading. This overloading alters joint mechanics and reflex responses, further increasing the risk of falls and injuries [9, 16].

During late stance, dorsiflexion of the hallux tensions the plantar fascia (the windlass effect), elevating the medial arch, shortening the foot, and stiffening the midfoot; this tightening enhances plantar cutaneous and fascia-related afferent input and refines joint-position sense [16]. When windlass engagement is reduced—such as in feet with decreased arch stiffness or under head-loading—the associated sensory reinforcement is blunted, increasing reliance on proximal (hip-trunk) balance strategies [9, 16, 27]. For instance, individuals with pes planus lose critical sensory feedback from their feet, exacerbating balance deficits [16]. Chronic neuromuscular adaptations due to impaired proprioception can also lead to inefficient gait patterns, increased musculoskeletal strain, and long-term functional limitations [9, 23].

3.6 Long-term risks: Cervical spondylosis and spondylolisthesis

The cumulative impact of head-loading on the cervical vertebrae includes an elevated risk of developing degenerative conditions such as cervical spondylosis and spondylolisthesis. Cervical spondylosis, a condition characterised by the progressive degeneration of cervical vertebrae and intervertebral discs, is more prevalent among habitual head-loaders due to sustained compressive forces on the spine [1, 6–9, 17]. Symptoms include chronic neck pain, stiffness, and nerve compression, which may lead to radiculopathy if left unmanaged [8, 9, 16, 17]. Chronic muscle strain further exacerbates these symptoms, contributing to significant discomfort and reduced quality of life [22].

Spondylolisthesis, on the other hand, involves the forward or posterior displacement of one vertebra over another [16]. This condition can result from repeated mechanical stress and weakened spinal stability; in head-loaders, the compensatory hyperlordosis adopted to balance cranial loads places excessive stress on the lumbar spine, increasing the likelihood of spondylolisthesis [1, 9, 16]. The condition often presents with symptoms such as lower back pain, stiffness, and neurological deficits, including numbness or weakness in the lower limbs [1, 9, 16]. Without timely intervention, spondylolisthesis can progress, leading to significant spinal instability and disability [16].

Kurten and colleagues reported that head-loading external mass produces a decrease in the craniovertebral angle (CVA) [8]. The CVA is the intersection of a horizontal line passing through the seventh cervical vertebra's spinous process and a line drawn from the centre of the tragus to the seventh cervical vertebra's spinous process [16]. CVA is a postural alignment measure and should not be used as a diagnostic indicator of cervical spondylolisthesis. As shown in **Figure 8**, head-loading alters head-neck and trunk posture (changes in CVA and craniohorizontal angles, reduced acromion/ASIS heights, and increased anterior pelvic tilt) [7, 23, 24]. Irrespective of the direction of cervical postural change, head-loaders frequently report neck pain [1, 7–9, 23].

The way carrying heavy loads on the head affects the body such as misalignment of the neck and lower back, knee deviation, flat feet, and reduced body awareness demonstrates the global mechanical and sensorimotor stress placed on the locomotor system [1, 7, 9, 22]. Long-term risks, including cervical spondylosis and related degenerative change, underline the need for prevention and ergonomic risk reduction [1, 6, 7, 9, 17]. Addressing these challenges requires a multidisciplinary approach that combines education on safer load-carrying techniques, context-appropriate load reduction/redistribution and supportive devices (e.g. short-term cervical orthoses), and community-based rehabilitation and public-health programming [1, 9, 26, 28].

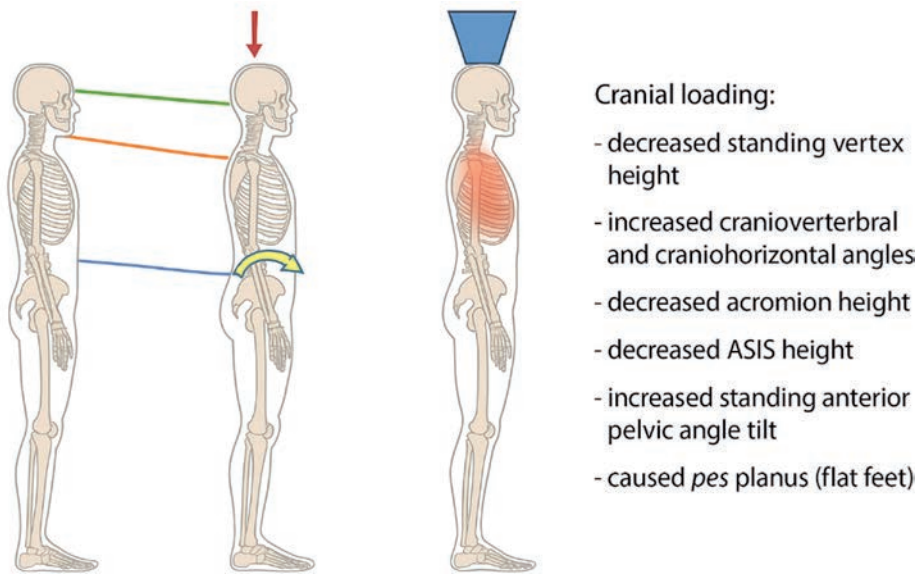


Figure 8.
Compensatory sagittal plane posture induced by head-loading [6].

By mitigating the adverse effects of head-loading, musculoskeletal health can be improved and quality of life enhanced in affected communities [1, 26].

4. The effects of the use of ergonomic interventions: From primitive ideas to modern solutions

The concept of using external devices to alleviate the physical strain of heavy loads is not a novel idea. Richard Benc's primitive designs for load redistribution in the early twentieth century laid the foundation for modern ergonomic interventions [29, 30]. Richard Benc, an engineer, theorised that by providing external support to critical weight-bearing structures, the body's biomechanical inefficiencies could be limited [29]. His early experiments with rudimentary support systems—though limited in sophistication—highlighted the potential benefit of assistive devices in reducing musculoskeletal strain and improving posture during load-carrying activities [29, 30]. **Figure 9** shows an illustration of the Richard Benc halo brace designed to assist porters while head-loading. Although Richard Benc was an engineer by profession, he used his knowledge and expertise in the medical profession of orthotics and prosthetics. There is no clinical evidence to determine whether Richard Benc's proposed halo-orthosis was validated [31].

Prosthetics and orthotics is an essential medical profession intricately involved in the rehabilitation of people with disabilities requiring an orthotic and/or prosthetic device [32]. In South Africa, contemporary development of the profession and its educational pathways has been recently documented [33]. Scope of practice and practitioner registration is regulated by the HPCSA [34]. Historical perspectives on orthotic and prosthetic education underpin current competency frameworks [32]. The process of manufacturing an orthotic or prosthetic involves architectural design, precise measurements, fabrication, and finally attachment of the orthotic or

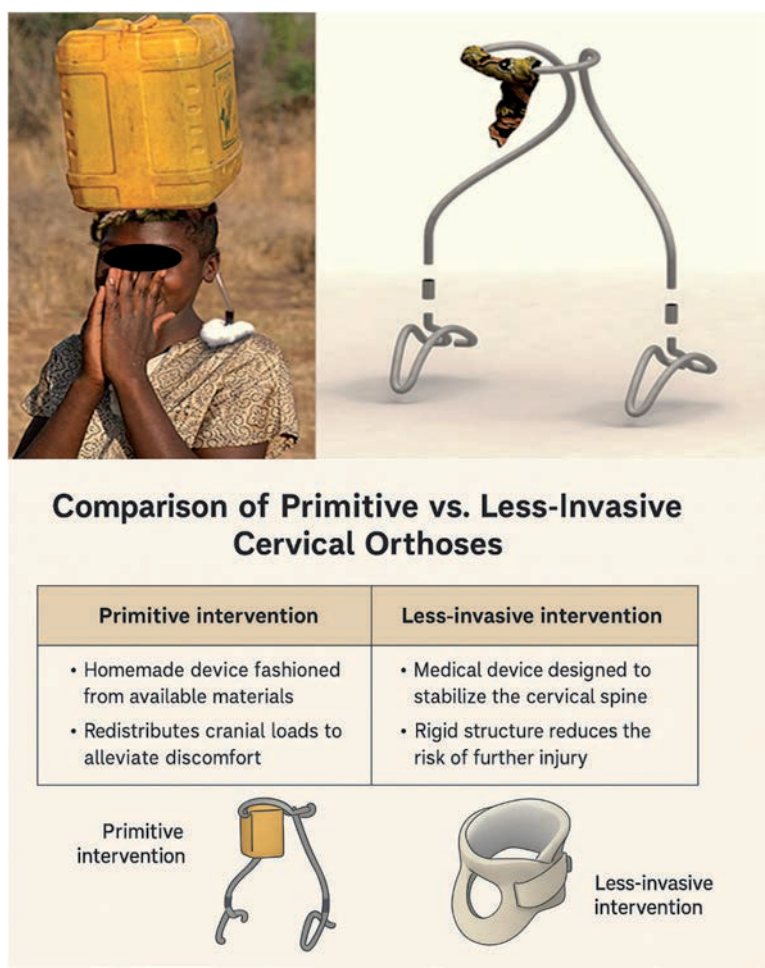


Figure 9.
Comparison of a primitive halo-style concept and a contemporary semi-rigid cervical orthosis.

prosthetic device to the musculoskeletal structure [35]. An orthotic device is a brace or other supportive device employed to correct the joint and postural alignment, reduce pain, and potentially provide the additional support to the body [35, 36]. A prosthetic device is employed to replace a missing limb. The profession of Prosthetics and Orthotics may seem new, but neuro-musculoskeletal rehabilitative devices have been utilised for many millennia [35, 36]. The earliest reports of orthotic and prosthetic devices were employed to realign bones and joints, and rehabilitate muscle injuries during the Iron Age, around 1200 BC [35, 36]. Over time, bone-setters evolved into the present day orthopaedic surgeons, while brace-makers progressed into medical orthotists and prosthetists [35].

This chapter's authors postulated, inspired by Benc's pioneering work, the idea of developing a semi-rigid cervical orthosis as a contemporary ergonomic solution. While Benc's designs primarily focused on addressing immediate load redistribution, advancements in material science and biomechanics have allowed for the refinement of his early concepts into more effective and user-friendly devices [1, 9, 16].

The semi-rigid orthosis improves upon Benc's initial ideas by incorporating modern knowledge about spinal biomechanics, proprioception, and muscle activation patterns [9, 16]. Unlike the primitive designs, which were limited in their adaptability and effectiveness, the semi-rigid orthosis is specifically tailored to stabilise the cervical vertebrae, promote healthy neutral postural alignment, and reduce long-term risks associated with repetitive load-bearing [1, 9, 16]. This transition from conceptual prototypes to evidence-based solutions underscores the evolution of ergonomic practices aimed at improving the quality of life in populations where head-loading remains a necessity [1, 26]. However, empirical investigations are still needed to validate its reliability [27].

By revisiting and refining the principles introduced by Richard Benc, this intervention pays homage to early ergonomic thinking and leverages contemporary scientific advancements to address the complex health challenges [1, 9]. A depiction of the cervical orthosis design and how it would be worn by users is provided in **Figure 10** below. A comparison of the earlier design to more modern orthosis design is provided in the same figure (**Figure 9**).

4.1 Semi-rigid cervical orthosis as an ergonomic solution

A semi-rigid cervical orthosis is designed to provide external support to the cervical spine, reducing strain on the vertebrae and surrounding muscles. By stabilising the cervical region, the orthosis redistributes cranial load toward the trunk/shoulders and reduces peak cervical moments, minimising compressive forces on the cervical vertebrae and the muscle activation needed to stabilise the head under load [1, 10, 16, 18]. The orthosis can limit excessive cervical protraction and retraction often seen in habitual head-loaders, promoting a healthier postural alignment during load-carrying activities [1, 16, 23].



Figure 10.
Pubescent female carrying a load while wearing a semi-rigid cervical orthosis.

The primary benefit of the semi-rigid cervical orthosis is its potential to reduce musculoskeletal pain and help prevent downstream neuro-musculoskeletal complications. By providing structural support, the orthosis may reduce the risk of vertebral malalignment that is associated with chronic neck pain and degenerative change (e.g. cervical spondylosis) in head-loading populations [1, 6, 9, 16, 17]. Improved proprioceptive control is also relevant for individuals navigating uneven terrain; augmenting head-neck stability can support balance and reduce loss-of-balance events [9, 16, 27].

The cervical orthosis can reduce muscle fatigue in the cervical and upper-back regions by decreasing demand on neck extensors and shoulder stabilisers, which is consistent with observed changes in muscle activity/posture under cranial loads and with load-redistribution ergonomics [10, 18, 23]. By avoiding excessive tissue strain, the device may help maintain long-term muscle and joint health and may lower the likelihood of wear-and-tear problems associated with repetitive head-loading [1, 9, 16].

In addition to mechanical benefits, a semi-rigid orthosis can function as a postural training aid. By promoting a neutral head-on-neck position and providing tactile/afferent feedback, it may facilitate motor re-education and more efficient load-carrying biomechanics over time [9, 16, 27]. Unlike rigid immobilisers, the semi-rigid design offers a balance between support and mobility, allowing users to maintain functional head movement for daily activities an important practical consideration in rural contexts [16]. Appropriate sizing and adjustable liners enable individualised fit, supporting comfort, adherence, and clinical effectiveness. The orthosis also serves as a non-pharmacological pain-management adjunct for people with chronic cervical discomfort. In low-resource settings with limited access to medication, such an approach can be cost-conscious and scalable within community programmes [1, 9, 26]. The device can be used both as a preventive public-health intervention and as a rehabilitative aid in clinical or outreach settings, including among adolescent females at higher postural risk [9, 24, 26].

Overall, a semi-rigid cervical orthosis represents a practical, context-appropriate ergonomic option with the potential to enhance muscle and joint health for people who regularly carry head-borne loads [1, 10, 18]—though population-specific empirical validation remains necessary [27].

4.2 Summary of potential health impacts and benefits of the cervical orthosis

Table 1 presents our interpretive synthesis: Based on prior evidence that head-supported loads alter cervical mechanics, muscle demand, posture, and balance [1, 9, 16], we outline the *anticipated* effects of a semi-rigid cervical orthosis as a clinical translation of load-redistribution principles [10, 18]. These proposed benefits (e.g. promoting neutral head-neck alignment, sharing load toward the shoulders/thorax, supporting proprioceptive control) are hypothesis-driven and intended to guide practice and research; population-specific validation remains necessary [27].

4.3 Practical considerations for implementation

The successful adoption of cervical orthoses in rural communities hinges on accessibility, cultural relevance, and functional usability. Because head-loading is deeply embedded in daily routines particularly for women and adolescents—any intervention must be practically viable and socially acceptable. To support adherence, the orthosis should be lightweight, durable, comfortable for extended use, and able to accommodate varied anthropometrics and load magnitudes [16, 35, 36].

Health impact of head-loading	Description	Effect of cervical orthosis
Cervical spine issues and vertebral Misalignment	Compressive forces on cervical vertebrae cause alignment issues, forward head posture, and strain.	Stabilises the spine, redistributes the load, and reduces vertebral misalignment.
muscle strain	Neck and shoulder muscles (e.g. upper trapezius) are overactive, leading to fatigue and discomfort.	It reduces muscle activation and fatigue and improves endurance.
Postural deviation	Continuous load-carrying causes a forward head tilt and rounded shoulders.	Enhances postural alignment and prevents excessive cervical flexion.
Proprioceptive impact	Reduced balance and proprioceptive control, especially on uneven terrain, can increase fall risk.	Improves balance and proprioception, reduces the risk of falls.
Pulmonary function	Potential respiratory restriction due to load on chest and neck.	Does not restrict respiratory capacity, allowing comfortable breathing.
Long-term musculoskeletal risks	Increased risk of cervical spondylosis, chronic neck pain, and potential nerve compression.	Reduces long-term risk of degenerative conditions and chronic pain.
Spinal load transfer	Axial load from the skull is transmitted vertically through the cervical spine, increasing joint stress.	Orthosis redistributes load across the shoulders and thoracic region, reducing focal stress.
Adolescent skeletal vulnerability	Early onset of head-loading may impair vertebral development and spinal curvature in children.	Provides developmental support during growth, helping prevent long-term postural abnormalities.
Energy expenditure	Increased EMG activity in cervical muscles increases fatigue and metabolic cost.	Reduces unnecessary energy expenditure by supporting load mechanically.

Table 1.
Summary of the adverse health impacts of head-loading and the potential benefits of the use of a semi-rigid cervical orthosis.

Evidence from field reviews shows that ergonomic interventions work best when co-designed around local customs and daily practices; devices that integrate seamlessly into routine tasks and do not restrict range of motion have higher uptake [1, 26]. A modular design with adjustable components and multiple sizing options can improve fit, comfort, and usability key determinants of consistent use [35, 36].

Community education is equally vital. Local health workers, educators, and community leaders can shape public perception through demonstrations, hands-on training, and clear messaging about short- and long-term benefits (reduced spinal strain, pain, and injury risk). Culturally appropriate visual aids, translated instructions, and follow-up visits help build understanding and trust [26].

Integrating the orthosis within school health or outreach programmes may further increase uptake. Adolescents at risk for long-term postural deviations due to early head-loading are a priority group for preventive efforts [7, 9, 24]. Overall, coupling accessible device design with culturally sensitive education can foster sustainable preventive practice in head-loading communities, supporting physical resilience and aligning with broader public-health goals in low-resource settings [1, 26].

4.4 Effects on muscle function

It is hypothesised that introducing a semi-rigid cervical orthosis will improve muscle function in the neck and shoulder girdle by reducing peak cervical moments and sharing load toward the shoulders/thorax. Head-loading without support elevates neck-shoulder muscle demand and alters posture/muscle activity patterns [1, 10, 23]; therefore, an orthosis that promotes neutral head-on-neck alignment should lower extensor and upper-trapezius activation required for head stabilisation [1, 9, 16]. In practice, this would be expected to manifest as reduced EMG amplitude (RMS) in cervical extensors and upper trapezius, improved fatigue resistance (e.g. slower median-frequency shift), and lower perceived exertion during load carriage [10, 18, 23]. Enhanced afferent feedback from a supported, more stable head-neck segment may also refine motor control and decrease compensatory co-contraction [9, 16].

Evaluation note (for future/on-going work): A crossover assessment (with vs. without orthosis) during standardised head-loading could quantify effects using surface EMG of splenius/semispinalis capitis, upper trapezius, sternocleidomastoid, and thoracic erectors; secondary outcomes might include craniocervical angle, load-distribution proxies, and ratings of fatigue/discomfort and patient-reported musculoskeletal pain [1, 10, 16, 18, 23, 37]. As population-specific trials are limited, these muscle-function benefits should be regarded as hypothesis-driven and consistent with the established biomechanics/ergonomics rather than confirmed clinical effects [1, 9, 27].

4.5 Improvements in posture and kinanthropometrical measures

Kinanthropometrical measurements assess changes in body proportions, joint angles, and alignment. During head-loading, alignment shifts as the cervical spine experiences added compression, often presenting as forward head posture with reductions in cervical lordosis; compensatory adjustments such as increased lumbar lordosis and knee hyperextension may emerge to maintain balance, raising musculoskeletal stress [6, 8, 23, 24].

When unloaded, the body generally returns toward neutral; however, habitual head-loading can leave residual deviations (e.g. persistent head-neck posture changes and altered lumbar curvature) consistent with chronic adaptation to repetitive mechanical strain [1, 7, 23]. It is postulated that a semi-rigid cervical orthosis, by stabilising the cervical segments and promoting neutral head-on-neck alignment, may limit these compensations during load carriage and support healthier overall alignment [1, 9, 16]. Further population-specific studies are required to determine whether such biomechanical adjustments translate into lower long-term risk of cervical spondylosis and other musculoskeletal disorders [27].

4.6 Enhanced proprioception and balance

It is postulated that a semi-rigid cervical orthosis could enhance balance—particularly in the medial-lateral plane—by promoting a more stable head-on-neck alignment and reducing the corrective muscle activity required during head-loading [1, 9, 16]. Mechanistically, cervical stabilisation would be expected to (i) lower head oscillation and the need for high-gain neck-shoulder co-contraction, (ii) improve sensory integration by delivering a steadier visual and vestibular signal (less “noisy” head motion), and (iii) indirectly support plantar/arch afferents *via* more consistent

loading through the kinetic chain—effects that together could sharpen postural set and reactive control [1, 9, 16]. These changes should be most apparent on uneven terrain, where medial-lateral control limits balance [1, 9, 26].

Operational expectations (hypotheses): During standardised head-loading, the use of the orthosis is expected to:

- Reduce force-plate centre-of-pressure (CoP) sway—particularly in the medial-lateral (ML) direction relative to anterior-posterior (AP)—and improve time-to-boundary; sway should also be lower during narrow-base and tandem stance/tasks [9, 16].
- Lower surface-EMG amplitudes of the cervical extensors and upper trapezius at a given load and walking speed, indicating decreased stabilisation demand [10, 16, 18].
- Improve the craniovertebral angle (CVA) toward neutral (without restricting necessary motion), reflecting a more economical head-neck posture under load [1, 23].
- Decrease perceived exertion and reduce balance “near-misses” during obstacle/uneven-ground negotiation relevant to rural tasks [1, 26].

A suggested evaluation protocol for future work would involve using a crossover design (with vs. without orthosis) under task-relevant loads. This would include instrumented balance testing—force-plate centre-of-pressure (CoP) sway and time-to-boundary—short-walk perturbation tasks, and surface EMG of the splenius/semispinalis/upper trapezius. Concurrent kinanthropometry (craniovertebral and craniohorizontal angles) and patient-reported outcomes would be collected for perceived stability and discomfort [1, 10, 16, 18, 23, 27]. Additionally, pre-specified minimal clinically important differences for sway and symptom measures would be used to link biomechanical change with functional relevance [27]. Context and confounders to plan for would include results dependant on load magnitude and container geometry, terrain, footwear/foot posture (e.g. pes planus), training/adaptation, and device fit/adherence; co-designed education and fit-for-purpose sizing, which are all essential for real-world effect and uptake [1, 9, 26, 35, 36].

The bottom line or perspective of the study would demonstrate that enhanced balance and proprioceptive control with a semi-rigid cervical orthosis is plausible, with testable outcomes consistent with cervical biomechanics and load-redistribution ergonomics [1, 10, 16, 18].

5. Implications for public health and practical applications

Head-supported load carriage is common in many rural settings and is associated with musculoskeletal pain, postural deviation, and functional burden, which collectively strain households and local health systems [1, 2, 22, 26]. Exploring a semi-rigid cervical orthosis as a prophylactic aid is therefore a public-health question as much as a clinical one. In principle, a device that promotes neutral head-on-neck alignment and shares load toward the shoulders/thorax could reduce symptoms and longer-term risk in habitual head-loaders [1, 9, 16].

From an implementation standpoint, the most promising pathways pair the device with community co-design, education, and task-appropriate load management, delivered through school health and outreach programmes where water and commodity carriage is routine [1, 26]. Practical features such as light mass, durability, adjustable sizing, and comfort are essential for adherence [35, 36]. Because adolescents are at particular risk for postural adaptations, they represent a priority group for prevention [7, 24].

A prospective evaluation of a semi-rigid cervical orthosis in rural female head-loaders can establish feasibility and effect on alignment and symptoms; methods should include posture metrics (e.g. CVA), balance/proprioception outcomes, and user-centred acceptability to link biomechanics with health impact [9, 16, 27]. Given the extensive literature on Himalayan and Nepalese porter populations, subsequent external validation should test transferability to Asian contexts [3–5].

If successful, such a programme could contribute to equity-focused, low-cost risk reduction, complementing water-access and transport interventions already linked to health improvements in similar communities [1, 2, 26].

6. Conclusion

In conclusion, while this prospective ergonomic solution to the detrimental effects of head-loading needs empirical validation, it has potential benefit to head-loading porters. The cervical orthosis provides essential support to the cervical vertebrae by redistributing cranial loads, reducing muscle strain, and promoting better postural alignment. These theoretical benefits highlight the positive impact of ergonomic interventions on musculoskeletal health. The orthosis could help alleviate neuro-musculoskeletal challenges associated with head-loading, such as neck pain, muscle fatigue, and the development of degenerative conditions like cervical spondylosis, which are prevalent in communities that rely on this practice.

Although these benefits are yet to be validated through large-scale studies, the theoretical framework for the orthosis' effectiveness is based on scientific postulation. It is critical that future research rigorously investigates the impact of the cervical orthosis on various factors, such as load type, duration, environmental conditions, and long-term effects on musculoskeletal health. Understanding how the orthosis can be optimised for different communities and settings will be essential for its widespread adoption.

Furthermore, assessing the potential cost-effectiveness of the orthosis relative to alternative interventions will be crucial for healthcare decision-makers. It may also be easier to integrate the orthosis into daily life if industry stakeholders collaborate to improve its accessibility and design. Researching the usefulness and acceptability of the orthosis across various demographics will ensure it addresses the varying demands of users. Furthermore, continuous monitoring and assessment of the orthosis in practical environments will be essential for pinpointing areas for enhancement and guaranteeing its sustained efficacy.

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thank CoAfrica for the use of a photograph included as Figure 2 (“Africa Women carry baskets on their heads...”), available at: https://coafrika.org/wp-content/uploads/2022/08/IMG_0541-e1659733571755.jpeg (© CoAfrica, 2022).

Several conceptual illustrations were created by the authors using OpenAI DALL·E (2025) to assist in reproducing and clarifying key biomechanical concepts; prompts and post-editing were performed by the authors, who take full responsibility for the accuracy and interpretation of these images.

Conflict of interest

The authors declare no competing financial or non-financial interests. The authors have no affiliations with or involvement in any organisation or entity with any financial interest (such as honoraria, educational grants, participation in speakers’ bureaus, membership, employment, consultancies, stock ownership, or other equity interest, and expert testimony or patent-licencing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this chapter.

A.Appendix

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B.Appendix

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Table B1.
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C.Appendix

See **Table C1.**

Symbol/term	Definition
Anterior pelvic tilt	A forward rotation of the pelvis that increases lumbar lordosis and may affect spinal posture.
Cervical spondylosis	Cervical degenerative conditions that can lead to neck pain, stiffness, and nerve compression.
Craniovertebral angle (CVA)	The angle formed between the horizontal plane and a line drawn from the tragus of the ear to the C7 spinous process; used to assess head posture.
Cultural ergonomics	The consideration of cultural practices in designing ergonomic interventions.
Electromyography (EMG)	A technique used to measure electrical activity produced by skeletal muscles, often used to assess muscle function.
EMG Activity	The measurement of muscle electrical activity indicating muscle engagement or strain.
Head-loading	A traditional method of load transport involving placing weight on the cranium, common in rural African communities.
Kinanthropometry	The scientific study of body composition, size, and shape, particularly in relation to physical function.
Load-carrying biomechanics	The study of body mechanics and postural effects during external load carriage, particularly on the head.
Musculoskeletal fatigue	A condition where muscle performance declines due to prolonged load-bearing or overuse.
Orthosis	A medical device designed to support, align, or improve the function of a body part, often used to manage musculoskeletal issues.
Proprioception	The body's ability to sense its position, movement, and balance, critical for maintaining stability under load.
Pulmonary function	The respiratory system's ability to move air in and out of the lungs effectively.

Table C1.
Glossary of terms.

Author details

Chanelle Ribeiro-Wagener*, Terry Jeremy Ellapen and Yvonne Paul
Tshwane University of Technology, Pretoria, South Africa

*Address all correspondence to: ribeiro-wagenerc@tu.ac.za

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Chapter 3

Upper Limb Prosthesis: Advancement and Challenges

Amit K. Vimal, Shivani Sharma and Anoop Kant Godiyal

Abstract

Upper limb prostheses have undergone significant advancements in recent decades, with the notable improvements in functionality aimed at enhancing the quality of life for individuals with upper limb amputations. This chapter explores the evolution of upper limb prostheses, highlighting the key achievements in restoring functionality and the ongoing challenges in replicating the complex movements and sensory feedback of the human hand. It addresses the critical need for comprehensive rehabilitation interventions designed to optimize the functionality and independence of amputees while addressing post-amputation health concerns. From basic prosthetic designs like hooks to advanced myoelectric and bionic limbs, the technological progression in prosthetics has greatly expanded. Incorporating biofeedback mechanisms has further improved control, self-management, and overall user autonomy. This chapter provides the details of amputation prevalence, the history of prosthetic development, the classification of upper limb prostheses, and the latest innovations in prosthetic technology. The discussion also outlines current challenges in the field, offering valuable insights for researchers, clinicians, students, and individuals living with limb loss.

Keywords: upper limb prosthesis, bionics, rehabilitation, amputation, artificial limb

1. Introduction

The arena of biological sciences has been broadening to a great extent with advances in science and technology. The work regarding the amalgamation of the two sectors over the years has led to the development of finer rehabilitation sources. According to the World Health Organization (WHO), the word rehabilitation is defined as “a set of interventions designed to optimize functioning and reduce disability in individuals with health conditions in interaction with their environment” [1]. The field of sciences is not confined to medicine, surgery, or therapeutic measures but to resolving the individuals’ suffering health scenario and providing them with at most care, protection, prevention, improved quality of life, self-management, and independence. According to WHO data, globally, an estimated 2.4 billion people are currently living with a health condition that may benefit from rehabilitation [2].

Technologies and science play a crucial role in bridging the gaps and improving the treatment strategies for rehabilitating the health condition of amputations.

1.1 About the emerging field of prosthetics and orthotics

In 1989, the International Standards Organization (ISO) endorsed standardized terms to describe Orthosis and Prosthesis (ISO 8549-1:1989) which was then replaced in the second edition in 2020 stated the description of prosthesis and orthosis [3]. A prosthesis is defined as “externally applied device used to replace wholly, or in part, an absent or efficient limb segment” and it also includes “any such device attached to a component within the limb for structural or functional purposes, for example, bone-anchored prosthetic devices. An orthosis is stated as “externally applied device used to compensate for impairments of the structure and function of the neuro-muscular and skeletal systems” [ISO 8549-1:2020(E)] [3]. The abnormal biomechanics, physical, psychological, and vocational implications can occur in a person with any age group resulting from limb loss due to amputation, neurologic, orthopaedic, and musculoskeletal pathology. All of these underlying conditions must be considered when prescribing an orthosis and prosthesis to meet an individual’s personal goal and expectations [4].

In the current scenario, the technical development of the upper limb prosthesis for the person with amputation has completely changed in the last decade. It has focused on achieving the human limb’s functionality as soon as possible.

1.2 Upper limb prostheses

The upper extremity is a highly complex structure with muscles, bones, lymphatics, and neurovascular bundles that together contribute to creating an extremity that performs our everyday activities. The upper extremity also requires a great range of motion (ROM) to attain several positions involving various types of power and precise grips to perform daily activities. It has been estimated that the prevalence of amputation will double in 2050, from 1.6 million people in 2005 [5, 6]. A retrospective study of 2 years in Kolkata, India, stated that the prevalence of upper limb amputation accounted for only 5.2% compared to lower limb amputation, which later accounted for 94.8%. Among all the upper limb amputation cases, above-elbow amputations were most common, followed by below-elbow amputations [7]. For the upper extremity, the leading cause of amputation is trauma, with prolonged ischemia after traumatic injuries or even traumas that lead to excessive blood loss. The second most prevalent cause is recurrent cancer/malignancies and vascular diseases. The level of upper limb amputation is performed as distally as the fingertip and as proximally as the shoulder [8]. These amputations are named by the level at which the amputation has been performed (**Figure 1**). The functional status of the amputee is severely compromised with a higher level of amputation. In ascending order, the levels of amputation are: trans-phalangeal (finger amputation), trans-metacarpal (partial hand), trans-carpal (partial hand), wrist disarticulation, trans-radial (below elbow), elbow disarticulation, trans-humeral (above elbow), shoulder disarticulation (SD), and interscapulothoracic (forequarter) [10].

The loss of a hand or arm has severe challenges that could permanently impair the working status, quality of life (QOL) and independence of an amputee. Upper extremity amputation is considered threatening to individuals who rely upon fine motor skills and the use of dexterity to perform most work-related activities [11].

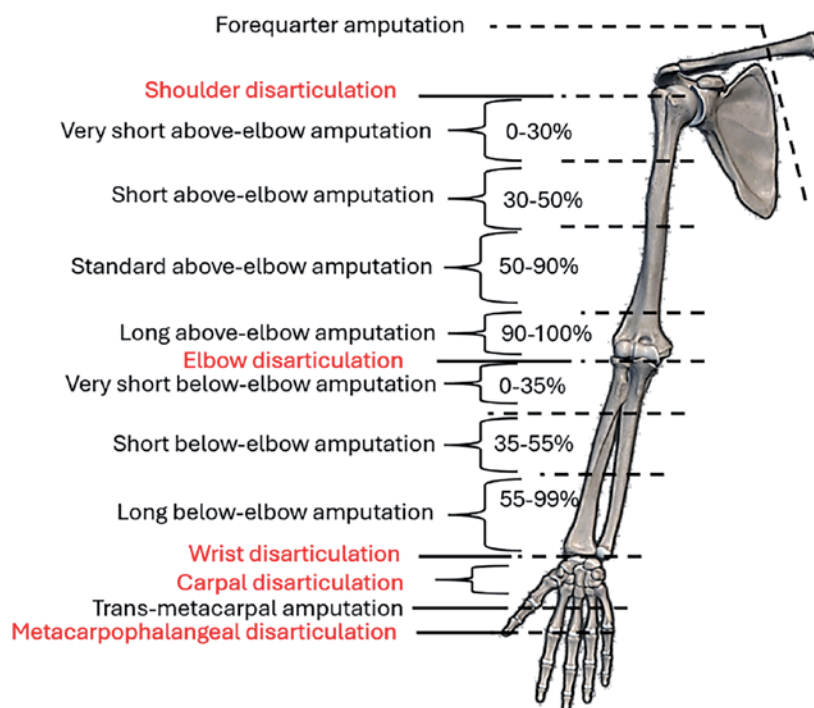


Figure 1.
 Overview of upper extremity amputation levels, used in clinical assessment and prosthetic planning: Authors' original work (upper limb bone figure is adopted from the public domain [9]).

Prosthetic restoration is an integral goal for these individuals to rebuild their social, psychological, emotional, and functional status. It has been found in the literature that, depending on the amputation level, prosthesis usage/acceptance in upper limb amputees ranges from 9 to 81% [12].

2. Evolution of upper limb prosthesis

Prosthetic limbs have a long history running from hooks, peg legs, and sleeve fillers to the development of the first powered prosthesis and in today's world of increasing demand for human-machine interaction technologies to fulfil individual needs and requirements. It began with one of the most famous examples of early hand prosthesis for the user named German Knight, Götz Von Berlichingen (1481–1562), who lost his hand at the age of twenty-three after being hit by a cannon fire, so an artisan made an iron hand with multi-joined digits that can be flexed or extended passively at the metacarpophalangeal, proximal interphalangeal, and distal interphalangeal joints including thumb interphalangeal joint (**Figure 2**). This hand has a single axis to open and close, and a lock with a button release. The device was modelled as an extension of battle armour rather than a human hand, so it is attached to Götz armour using thick leather straps [14]. The first recorded concept of “body-powered actuation” in upper limb prosthesis was made in 1812. A German Dentist named Peter Baliff created a functional limb prosthesis that allowed the amputee to use the prosthetic hand independently of its contralateral side; this feature was absent in previous designs

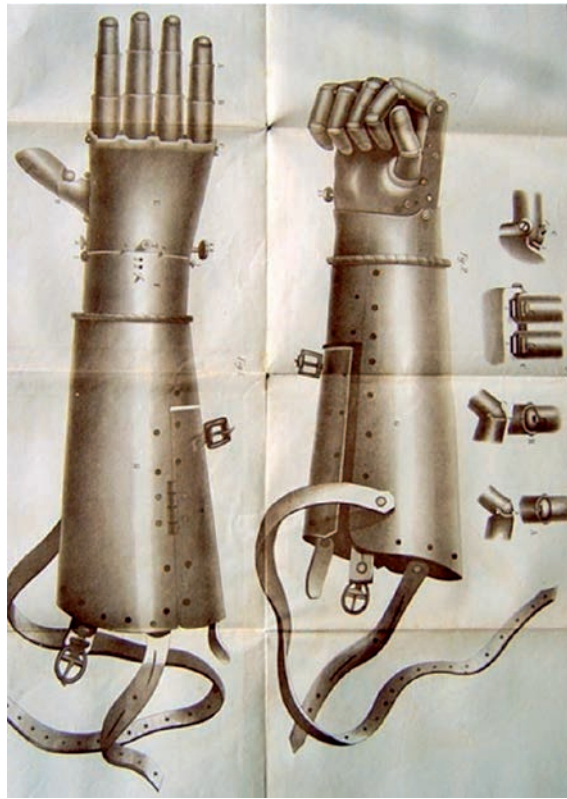


Figure 2.

Famous Iron hand of Götze von Berlichingen has a socket and leather straps that fit over the residual limb and keep the prosthesis on the arm. Source: Ref. [13].

because they were dependent on the sound side to actuate or lock the prosthetic hand functionality [15].

In 1906, William T Carnes of Pennsylvania lost his arm in a machine accident. He designed and made an artificial limb named “Carnes Artificial Arm”, shown in **Figure 3(a)** and **(b)**, which was designed as a mechanical prosthetic hand operated with a shoulder cable harness. The hands were articulated digits able to move simultaneously in a flexion mechanism as cable excursion is created through body power. The design was further modified in 1912, when an additional mechanism was added to lock and rotate the wrist [15].

The year 1948 led to the development of “Bowden Cable body-powered prosthesis” which replaced the bulky straps with a more sturdy and sleek cable system. This allowed the amputee to work with a better range of motion, speed, and force to exert the motion of the terminal device. Preserved shoulder and body movements generated tension in the cable system, which further operated the finger of the prosthesis, diminishing the use of the sound side to operate the prosthesis [14].

Due to the specific features of being lightweight, reliable, low cost, and mechanically simpler in design, the body-powered prosthesis is widely popular among upper limb amputees. As compared to externally powered prostheses, they

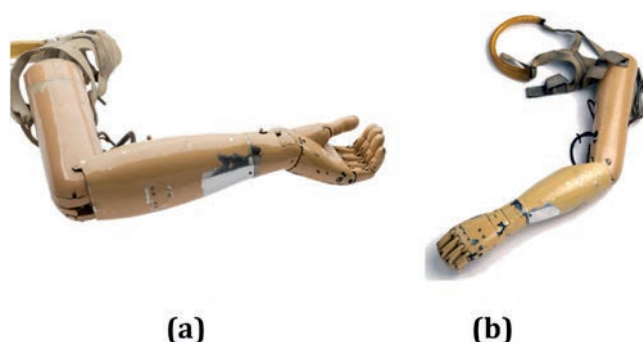


Figure 3.
 (a) Carnes artificial arm, (b) shoulder strap for Carnes. Source: Ref. [16].

tend to provide increased proprioception as the user feels the tension exerted while operating the cable mechanism. Apart from this, body-powered prostheses allow different types of voluntarily controlled terminal devices to be attached to the system, to attain fine prehension tasks using hooks or power grips using hands. Despite these advantages, body-powered systems require the amputee's force and effort to control the mechanism, making a higher level of amputee find extreme difficulty in generating the excursion force for the cable mechanism. Often, these types of common challenges faced by many amputees while using body-powered prostheses, along with the contralateral shoulder harnessing system, tend to create discomfort under the axilla of the sound side. Apart from these challenges, today, it still holds a vital role in the lives of many upper limb amputees [17]. The evolution of electric-powered prostheses also simultaneously came into light, with the first powered prosthesis being a pneumatic hand, which was patented in Germany in 1915, also known as a compressed-gas powered hand, which was not successful in terms of abundant usage. Furthermore, development work continued. Later in the early 40s, Reinhold Reiter, a physicist who published his work in 1948, developed the first myoelectric prosthesis. **Figure 4** shows the first myoelectric prosthesis used around 1943, a vacuum tube amplifier controlled the design, which was not a handy or portable design and was not battery-operated [19].

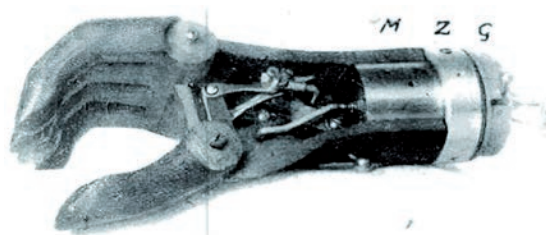


Figure 4.
 Electric-powered hand used by Reiter and become the first myoelectric prosthesis consisting of a Hüfner hand with a control magnet. Source: Ref. [18].

3. Classification of upper limb prosthesis

3.1 Based on types of prosthesis

The upper limb prosthesis is broadly categorised into passive and active prosthesis as per various sources [20–22]. Furthermore, both the individual categories can be subdivided, where active prosthesis is classified based on its control and activation system—body-powered prosthesis (control is mechanical through cable system) and externally powered prosthesis (control is through external source and/or power actuators) [22]. Body-powered prosthesis uses the residual limb of the user to operate different types of prehensors and/or terminal devices, which can operate in mainly two modes: voluntary opening and voluntary closing modes. These voluntary opening/closing devices can either be in a hand-like or a hook configuration. The traditional hook is of split type with straight (lyre) or canted (slanted) configuration. Generally, lyre-type hooks are for fine prehension (like picking a needle), and canted hook type allows the user to attain visual sight with side approach prehension (like using a pen) [17, 23] apart from these traditional hooks, another specific type of hooks, such as contour hooks or C-shaped, are commercially available to perform cylindrical grasping [17]. On the other hand, Maat et al. classified passive prostheses into passive hands and passive tools as per their functionality, the former function to provide cosmetic restoration and later designed to perform a specific activity [20]. The complete classification table is depicted in **Figure 5**.

In active prosthesis, the force applied to operate the artificial arm, hands/hooks or terminal device (TD) or the grasping mechanism is applied internally either through a body-powered cable mechanism and/or a combination of muscle unit actuation with

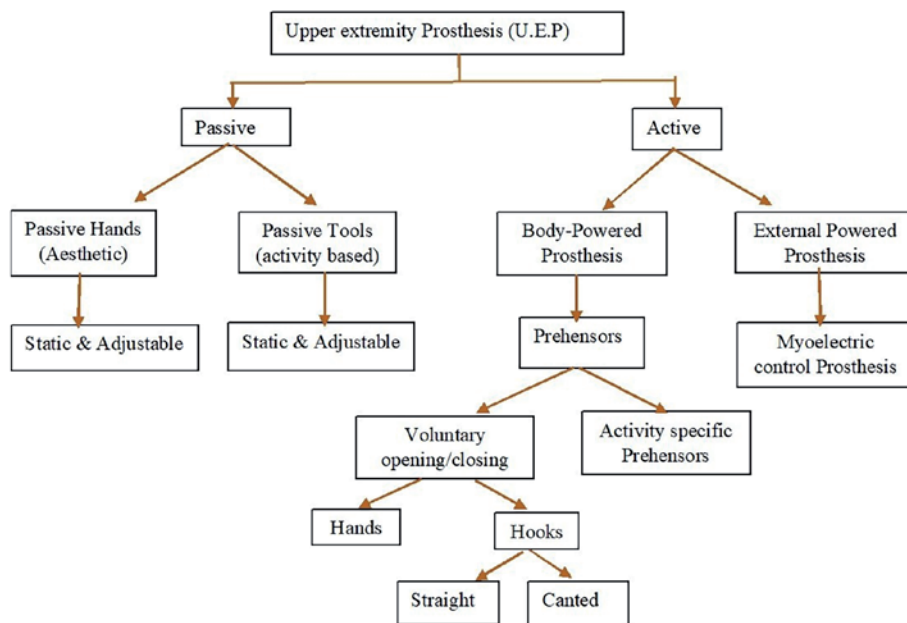


Figure 5.
Classification of upper limb prosthesis.

electrically powered switches. In passive prosthesis, the force applied to operate the terminal device is externally, for example by the contralateral/sound hand [20].

Passive Hands are considered to be the most commonly prescribed Passive Terminal Device when cosmetic restoration is the prime motive of the patient and offers a life-like appearance, thereby providing either a static grasp or adjustable position through the sound limb. An example of a common static passive hand is “passive mittens”, which has combined fingers and is prescribed in a child’s case. This soft, flexible, humanoid, cupped-shaped human hand resembles children’s mittens generally recommended for infants and certain sports-related activities like swimming. On the other hand, Passive Standard foam hands or extended wire foam hands shown in **Figure 6(a)** and **(b)** are flexible-skinned, lightweight foam hands around a metal skeleton mounted on a plastic base. Therefore, individual digits can be positioned manually. A cosmetic hand, thereby, can be static or adjusted manually. When these passive hands are incorporated along with custom-sculpted cosmetic gloves made up of special silicone rubber, they give ultimate cosmesis [20, 25]. Passive tools are generally activity-specific and must be performed with both hands. They would rather have a more mechanical appearance than a cosmetic one, as some could have hooks at the terminal end. In contrast, others have activity-specific designs and do not hold a cable mechanism to operate [20].

Body-powered prostheses are a type of active category of upper limb prosthesis that has been widely used for centuries and is even prescribed today. The term itself is self-explanatory that the force required to operate the prosthetic components is exerted from the amputee’s body itself, mainly from the amputation site as per the adaptations of the *Bowden* design, also known as *Bowden housing cable system* with key feature of fixed length of cable housing to ensure the excursion force is adequately transferred from the harness to the terminal device shown in **Figure 7**. The key movements in a body-powered generation are glenohumeral flexion of the amputated side and bicipital abduction. Mechanically simpler design, low cost and lightweight features made its application widespread even after today’s technological advancements. Basic components involve the incorporation of a harness system that often encompasses the uninvolved shoulder, control cable mechanism, cable housing and terminal device (TD), which can be either

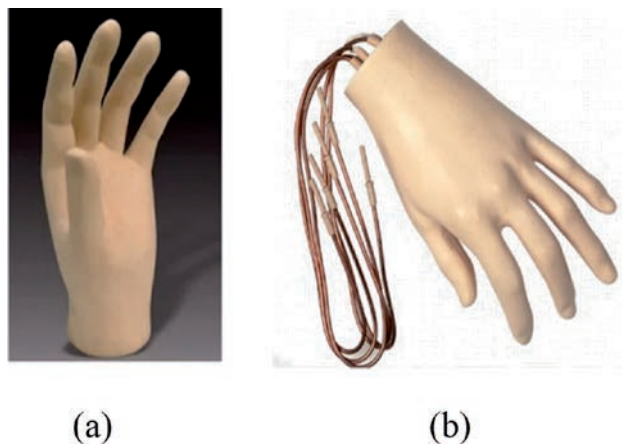


Figure 6.
(a) Passive Standard Foam Hands and (b) Passive extended wire foam hands. Source: Ref. [24].

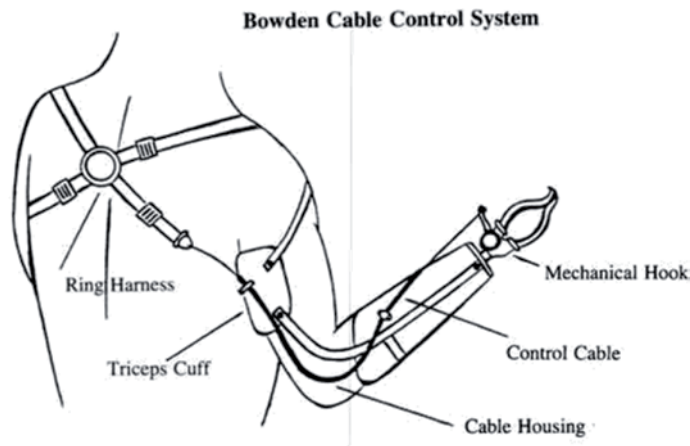


Figure 7.
Bowden cable body-powered prosthesis. Source: Ref. [26].

“Voluntary opening” or “voluntary closing” type of prehensors in the form of Hands or Hooks as shown in **Figure 8 (a)** and **(b)** [25].

3.2 According to input control

In active prostheses, the external mechanisms are incorporated to replicate muscular functions. These devices require essential components, such as an energy source, a force transmission system and a gripping mechanism, and are classified based on their actuation system [27]. Detailed information regarding the input control for the prosthetic upper limb is as follows:

- a. *Mechanical prostheses*: Operated by wrist or elbow movements (depending on the amputation level) that transmit force through cords to open or close the hand [28].
- b. *Pneumatic prostheses*: These use air compression to move mechanisms like pistons. However, they often require bulky accessories [19].



Figure 8.
(a) Voluntary Opening Hand (Steeper, UK). (b) Hook (Steeper, UK). Source: Ref. [24].

c. *Electric prostheses*: Powered by electric motors and batteries (typically rechargeable lithium). These are more costly to produce and need protection from humidity. Electric prostheses include various input methods:

- *Electromyography (EMG)*: Sensors detect muscle contractions by measuring potential differences. Electrodes can be placed directly on the muscles (for stable signals) or on the skin. While effective, EMG control depends on muscle condition and electrode placement [29].
- *Electroencephalography (EEG)*: Uses brain electrical activity to control the prosthesis *via* direct or surface electrodes. This advanced method shows promise for future developments but requires further research [30].
- *Force myography (FMG)*: Sensors measure muscle activity during contractions by detecting changes in muscle volume. This method experiences less electrical interference compared to EMG [31].
- *Near-infrared monitoring*: Measures muscle oxygenation and blood flow levels to produce high-resolution signals. Though still experimental, this method has potential for future applications [32].
- *Synergistic posture mapping*: Detects body orientation and contact forces. For example, a gyroscope can detect thumb position to control prosthetic fingers [33].
- *Targeted muscle reinnervation (TMR)*: TMR involves rerouting residual peripheral nerves, severed during amputation, to reinnervate the alternative muscle targets. These reinnervated muscles act as biological amplifiers, producing electromyographic (EMG) signals that can be harnessed to control myoelectric prosthetic devices. This technique not only facilitates intuitive prosthetic control but also mitigates neuroma formation and phantom limb pain by providing functional targets for nerve regeneration [21, 34].
- *Targeted sensory reinnervation (TSR)*: TSR is a surgical approach that redirects residual sensory nerves to reinnervate skin areas, enabling the restoration of sensory feedback in amputees. By providing sensory input from the prosthetic limb to the brain, TSR enhances the user's perception and integration of the prosthesis [35].
- *Implantable myoelectric sensors (IMES)*: IMES are miniature, wireless sensors implanted directly into residual muscles of amputees. These sensors detect electromyographic (EMG) signals generated by muscle contractions, which are then wirelessly transmitted to an external controller embedded within the prosthetic socket. This setup allows for more precise and natural control of prosthetic limbs compared to traditional surface electrodes [36].
- *Hybrid systems*: Combines two or more control methods, such as EMG and EEG, to enhance gesture prediction accuracy with artificial intelligence [37]. Hybrid systems can also integrate mechanical forces with EMG for simpler control mechanisms [32].

In modern prosthetics, surface EMG signals are the most commonly used for electronic prostheses. However, EEG-based controls are less common due to several challenges, such as high costs, limited cases requiring EEG (e.g. trans-humoral amputations where EMG signals are insufficient), and the lengthy training process for EEG calibration. Recent advancements in artificial intelligence are making EMG-based systems more intuitive and accessible, paving the way for more natural prosthetic control.

4. Advancements in upper limb prosthesis

Externally powered prostheses derive their energy from a source outside the body, typically utilizing electrical energy stored in rechargeable batteries. These prostheses rely on advanced control systems to enable functionality, with myoelectric control being the most prevalent. This system leverages the body's neuromuscular system to translate voluntary muscle activity into actionable control signals. The process begins with the activation of motor neurons in the spinal cord, which initiates a cascade of events leading to the contraction of muscle units (MUs). This synchronized activation produces composite action potentials that manifest as myoelectric signals, also known as electromyography (EMG). EMG is a technique used to record the electrical activity produced by skeletal muscles during contraction. EMG signals are captured either non-invasively through surface electrodes placed on the skin or invasively using needle electrodes inserted into the muscle. These signals are then processed to control the electromechanical terminal devices, such as prosthetic hands, wrists, or elbows. The EMG signal acquisition process involves the following steps (**Figure 9**):

- *Electrode placement*: Surface or intramuscular electrodes are placed over or within the targeted muscles. Surface electrodes are non-invasive and commonly used for prosthetic applications.
- *Signal amplification*: The raw EMG signals are weak (ranging from 0 to 10 mV) and require amplification using differential amplifiers.
- *Signal filtering*: Filters are applied to remove noise, motion artefacts, and power-line interference, typically focusing on a frequency range of 20–500 Hz.
- *Signal sampling*: The filtered signals are digitized using an analogue-to-digital converter (ADC) at an appropriate sampling rate, usually above 1 kHz, to ensure accurate representation.
- *Feature extraction*: Key features such as amplitude, frequency, and time-domain characteristics are extracted to encode muscle activity.
- *Signal processing*: Algorithms are applied to process the data for interpretation and control.

The application of EMG for prosthetic control has a long history, first being utilized in 1948 to control hand prostheses [38]. Over the decades, the technology has undergone substantial evolution, progressing through four distinct generations (**Figure 9**):

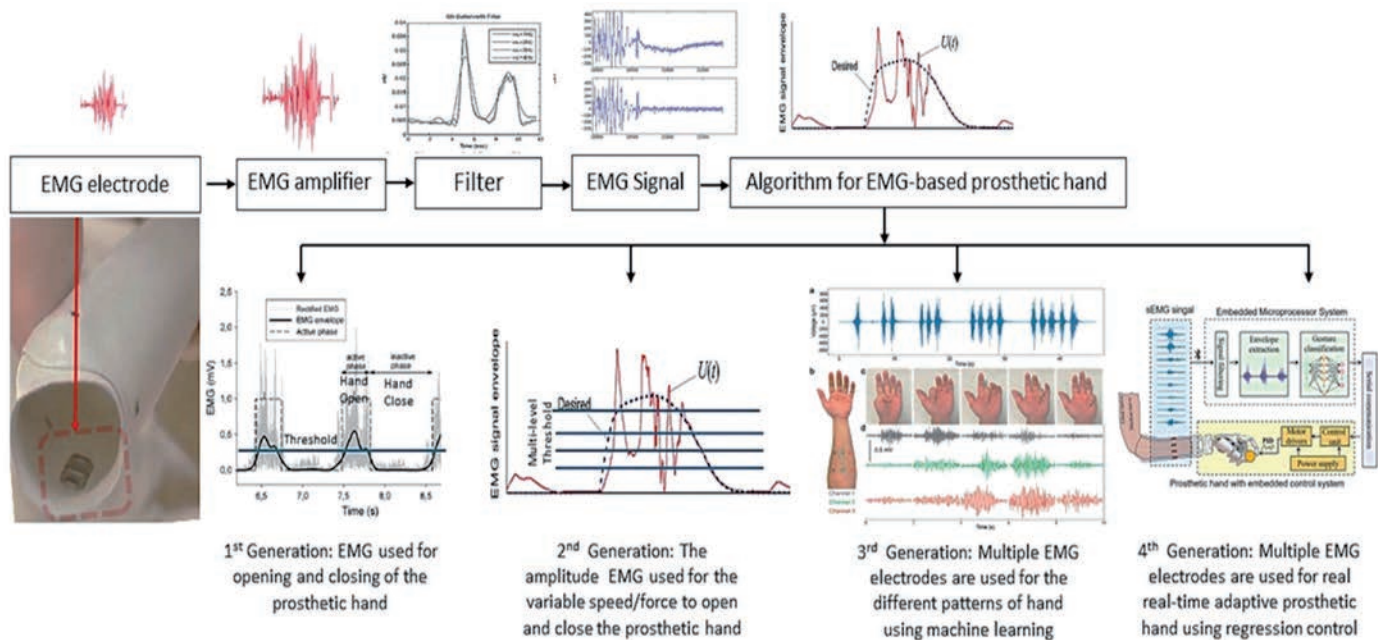


Figure 9.
 Advancement of myoelectric hand prosthesis. Source: Authors' original work.

- a. *First generation:* Basic on-off control systems using threshold-based signal processing. If the EMG signal of the contracting muscle crosses the threshold value, it will open the channel to operate the motor in either opening or closing the prosthetic hand.
- b. *Second generation:* Proportional control systems that allowed finger adjustments based on signal amplitude. In this generation, the speed and force of the prosthetic hand are controlled by the amplitude of the EMG signal. As a single grasp device has limited grasping, control, and manipulation capabilities, a multigrasp control interface approach was developed that enables the amputee to perform better daily living activities by providing a set of hand postures and grasps. The multigroup myoelectric controlled Prosthesis could able to perform the basic six grasps (tip, lateral, tripod, spherical, cylindrical and hook), including certain postures like pointing posture and palm posture by utilizing a standard, two-electrode EMG interface [39]. The multigroup myoelectric controller works by incorporating an event-driven finite-state control structure to coordinate the motion of digits. These states are the combination of postures and grasp mentioned above. These interconnected states are arranged as per the degree of hand closure. Generally, the amputee will navigate the state by four essential inputs, which EMG indicates at two electrode sites. The four inputs include flexion, extension, co-contraction and rest.
- c. *Third Generation:* Inclusion of multiple degrees of freedom using pattern recognition and machine learning techniques. In this generation, the positions of the fingers and the thumb with the EMG signals are used to train the system for performing a specific prosthetic position and for a particular signal. The third generation involves programmable microprocessors that allow an infinite range of adjustments of myoelectric-controlled devices. It allows complex filtering of signals, resulting in better responsiveness as it incorporates a pattern-recognition-based control system in which the functions are discriminated from signal patterns by classifiers. The classifier is trained to associate EMG input patterns with planned postures and grasps. During this operation, the classifier will examine each frame (moving windows in time) of EMG data and decide accordingly about the movement that is to be carried out; therefore, a variety of functions depends on the classification performance directly [39, 40].
- d. *Fourth generation:* Integration with advanced technologies like neural interfaces, deep learning algorithms, and real-time adaptive systems. In this generation, the prosthetic hand pattern is decided by the algorithm using multiple signal recognition. Regression control is a type of control strategy that simultaneously controls various joint angles. For example, two degrees of freedom (DOFs)—hand opening/closing and wrist pronation/supination—are controlled simultaneously from two channels of analogue signals obtained from the EMG signals using multivariate regression algorithms. Both the pattern-recognition-based myoelectric signal controller (MSC) and regression-based MSC allow multiple DOFs at the same time by either discrete or continuous means that first-generation and second-generation myoelectric prostheses cannot perform [41, 42].

Recent advancements in the field have incorporated high-density EMG (HD-EMG) and intramuscular sensors, enabling more precise and intuitive control. Additionally, innovations such as hybrid systems combining myoelectric and bio-mechanical controls, along with the use of artificial intelligence, have significantly improved the functionality, adaptability, and user experience of externally powered

prostheses. These developments represent a transformative leap towards achieving near-natural limb replacement capabilities.

The upper limb prosthesis has continuously proceeded towards advancement in terms of functionality over the last decades with significant improvement ranging from hand prosthesis with simple gripper-like devices with one degree of freedom to multifunctional prosthetic hands with multiple degrees of freedom like different grip types, wrist movements, or independent finger movement shown in **Figure 10(a)**. For upgradation, attempts were being made to control the joints of fingers so that dexterity could be improved. The Touch Bionic i-limb is a commercially available prosthetic device with five individually powered finger movements depending on the capability of the user. Even the different grips or positions that were not available in the prosthesis before it was introduced in i-limb due to the incorporation of a thumb that works like a human thumb to achieve different positions and to enable the important grip configurations [45].

Many other commercially available robotic hands offer multiple degrees of freedom and functional dexterity, which are alternatives to electric motors for actuation (e.g., LUKE Arm-Mobius Bionics, bebionic Hand-Ottobock, Modular Prosthetic Limb-Johns Hopkins APL, Genesis Hand-Alt-Bionics). Hydraulic or pneumatic-driven actuators offer high forces with low weight and more DOFs compared to the previous ones [46, 47]. One of the leading designs commercially available is the Shadow Dextrous Hand (**Figure 10(b)**) and is considered to be one of the very few highly dextrous robot hands, which is a sized hand offering 24 degrees of freedom, 20 of which are independently controlled. The hand allows each finger to be independently turned in the lateral direction, along with two separate DOFs for bending purposes. There is an extra DOF in the palm to attain the power grasp. It is available in two versions, McKibben pneumatic “muscle” actuator and an electric DC motor



Figure 10.
(a) Multifunctional prosthetic hands. Modified from the public domain image [43] (b) Shadow Dextrous Hand is considered to be the most dextrous humanoid Robot hand. Source: Ref. [44].

to pull the tendon. The modern version with DC motor provides improvements in tendon routing, providing smoother movements for dexterous actions to operate.

Until now, the only prosthetic option available for finger amputees were non-functional finger prosthesis, that is cosmetic silicone fingers but recent advancement was being made for individuals with partial hand amputation level by developing the first ever functional artificial finger prosthesis intended for amputation level distal to the metacarpophalangeal joint which is body-powered and was named as “X-finger” (**Figure 11(a)**) developed by Didrick Medical Inc., Naples, US [50]. Being body-powered, they are made up of stainless steel that allows independent finger movement using the residual hand. An attachment point is located at the base of the knuckle, which extends proximally into the palm. When the amputee flexes the residual finger, a polycentric linkage mechanism also flexes the prosthetic finger.

Another commercially available advanced body-powered finger prosthesis for partial hand amputation level developed by Partial Hand Solutions, LLC, named as “M-finger” (**Figure 11(b)**) is also intended for amputation-level distal to the metacarpophalangeal joint [51]. This finger prosthesis uses a cable mechanism attached to the dorsal surface of the hand. Metacarpophalangeal flexion creates excursion force in the cable, leading to the partial prosthetic finger flexing at the volar.

4.1 Challenges in upper extremity prosthetics

Upper limb prosthetics have evolved to a greater extent since the previous decades, whether in terms of accomplishing functionality, comfort, aesthetics and meeting the specific needs of users. To this day, we still trail behind in achieving prostheses that can be more biologically realistic. Despite of overcoming the complexities of the human hand through improved human-machine interaction gained multiple grasp patterns and recognition techniques to enhance the prosthetic controlling, the ultimate and complete natural movement restoration with fine motor dexterity is difficult even today due to limitations in control techniques, material science, and actuator design [52].

Specific technological challenges for upper limb prostheses are as follows:

1. *Complex grasping and manipulation*: It is a technological challenge in upper limb prosthesis to match the dexterity of a human hand and continues to be worked upon in order to incorporate advanced mechanisms and control interfaces and/

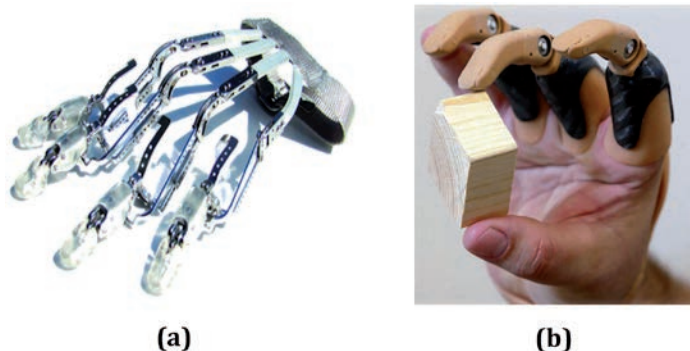


Figure 11.

(a) “X-finger” is the first body-powered artificial fingers developed by Didrick Medical Inc. These prosthetic fingers are considered to be the most dexterous, durable, low profile prosthetic finger. (b) Partial M-finger—functional finger prosthesis requires cable excursion to flex the Intephalangeal segment of the Prosthesis. Source: Refs. [48, 49].

or algorithms to achieve multiple grasping to handle objects with various sizes, shapes, and textures with greater efficiency.

2. *User customization*: When it comes to customising upper extremity prosthesis as per the individual preference to carry out specific tasks and recreational activities, it is a challenge as it majorly relies on professional expertise. Therefore, advancement in material sciences, new technologies, and its amalgamation will help to meet the unique needs and preferences of individual users.
3. *Sensory feedback precision*: The sensory substitution and proprioception are the major challenges to overcome in the present time to improve prosthetic control, as the restoration of missing sensation requires the use of either invasive or non-invasive interfaces to develop high-precision for touch and grip in upper limb prostheses. Until now, the sensory feedback has only been integrated in fewer high-end myoelectric prostheses [53] within the research level, and yet to come for consumer usage.

Another challenge addresses the limited number of options for the paediatric population with congenital upper limb deficiencies for fulfilling their active and growing needs in both functionality and cosmesis. Myoelectric pattern recognition-controlled prostheses that are commercially available to adults at present still hold back from reaching up to the paediatric population with similar limitations that fail to imitate human-like appearances [54]. The integrated involvement of artificial intelligence and virtual reality in the research areas can open new gates into the commercial land to bring out necessary outcomes for the users in real time.

5. Conclusion and future directions

The major advancements took place to meet the demands of individuals on the verge of reaching the normal, whether ambulating with variable cadence in a near-normal walking gait or performing fine tasks with five-finger movement. Since the last decade, advancements in the field of prosthetics have achieved up to the mark, but it has been concluded that there is still an opportunity left in trends/advancements.

Both the creation of upper and lower limb prostheses face substantial technological challenges. For example:

1. *Integration of sensory feedback*: After amputation, the missing sensory function to be restored remains a challenge. The inclusion of sensory feedback and proprioception into the prosthesis is the focus area of research and yet remains to be commercialized.
2. *Naturalistic appearance*: Similar to functionality, the cosmesis also plays a major role in the acceptance of prosthesis. Therefore, the advancement in technology has managed to achieve artificial limbs close to the natural human limb but still lags in functional resemblance.
3. *User control interfaces*: The reported rejection rate of using body-powered or electric-powered prostheses requires the technology to shift towards the usage of intuitive and reliable control interfaces, such as vibrotactile and electrotactile interfaces. The challenge lies in integrating such interfaces into myoelectric control or advanced prostheses for both upper and lower limb prostheses at a commercial level for improved control.

4. *Precision control*: Replicating fine motor skills, such as delicate finger movements or walking gait, is a challenge for upper and lower limb prostheses, respectively.
5. *Energy efficiency*: Maximizing energy efficiency and increasing power sources are necessary during prosthetic usage in order to ensure long-lasting and optimum functionality for either type of prostheses; this area of technology can always be improved or worked upon.

Addressing these challenges often involves interdisciplinary collaboration between engineers, prosthetists, and clinicians. Research and innovation in materials science, robotics, neuro-prosthetics, and artificial intelligence continue to drive the advancements in upper limb prosthetic technologies, improving the quality of life for individuals with limb loss, whether it is the discovery of new technologies or introducing the work of research into the commercial platform. The feedback system and brain-computer interface (BCI) based devices are still under research for the upper limb prosthesis level. Advanced bionics and five-finger movements are commercially available for upper limb prosthetics. However, more fine-tuning and precise movement, along with adequate speed, are required to reach consumer availability and are considered to be the challenges in upper limb prosthetics. As for future work, advancement will proceed in prosthetics by incorporating robotics, artificial intelligence (AI), and virtual reality into the devices. This amalgamation of sensors, electronic motors, processors, robotic joints, and AI will uplift the upcoming artificial limbs in future.

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Author details

Amit K. Vimal^{1*}, Shivani Sharma¹ and Anoop Kant Godiyal²

1 Pandit Deendayal Upadhyaya National Institute for Persons with Physical Disabilities, New Delhi, India

2 Department of Physical Medicine and Rehabilitation, All India Institute of Medical Sciences Delhi, Ansari Nagar, New Delhi, India

*Address all correspondence to: akvimalpo@gmail.com

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Chapter 4

Lower-Limb Amputation and Gait Abnormalities: Exploring Challenges and Technological Innovations

*Md Enamul Hoque, Md Sakif Zawad
and Nur Md Atiquzzaman Rasel*

Abstract

Amputation of the lower limb is a life-changing experience, affecting a person's walking, lifestyle, and daily routine activities. Although prosthetic limbs are made to replace the missing movement, they cannot mimic the natural walking mechanics. This usually causes discomfort, lack of balance, and additional energy consumption that makes performing even simple activities even more tiring. This chapter provides a focused literature review of existing challenges and the rising technologies in advanced lower-limb prosthetic development with a particular emphasis on biomechanics, smart control systems, and material innovation. Such technologies as microprocessor-controlled knees and energy-storing feet are being found effective in enhancing walking economy and addressing gait pathologies, yet usually with high costs and additional requirements of upkeep, therefore being less accessible. The custom contours of their 3D-printed sockets are simpler to produce, but are less achievable due to the constrained materials and associated limitations. A promising area is AI-supported feedback systems that can real-time adjust the alignment of the prosthetic and provide a more natural walking experience; however, the technology is currently limited by its cost and regulatory issues. In spite of this, the future of prosthetics is bright. The new technologies are making the prosthetics smarter, adaptive, and in the end, more comfortable. Future prosthetic design will aim to strike a balance between functionality, comfort, and cost, with energy-efficient feet and microprocessor-controlled joints being the most promising technologies to make people more mobile and less fatigued.

Keywords: ground reaction force (GRF), force sensing resistor (FSR), osteoarthritis, postural instability, adaptive technologies, mobility enhancement, brain-computer interfaces (BCI)

1. Introduction

The loss of the lower limb is not only a physical change; it also affects the life of an individual in many aspects that are, in most cases, impossible to comprehend. Following an amputation, walking may become difficult and tiring, and the unequal distribution of weight, rigid joints, and the need for more effort to make a single step are encountered. These issues can only be exacerbated with time unless they are handled appropriately [1, 2].

Although prosthetic limbs are invented to aid in the restoration of mobility, most of them still fail to match the natural movement of the human body. We have come a long way, but still, such prosthetics may be uncomfortable, stiff or just generally not fit a particular patient. This may cause users to be frustrated and even experience additional physical or emotional problems [3, 4].

This chapter reflects on the existing gaps in prosthetic design and how technological advancements improve support to amputees by introducing better functionality and comfort to the prosthetics. Prosthetics are becoming more personalized, with technologies such as microprocessor-controlled knees, 3D-printed bespoke sockets, and AI-enhanced feedback systems making them smarter, more versatile, and comfortable. These innovations not only enhance the functionality of the prosthetics but also empower amputees to live their lives more comfortably and freely, without being restricted by their prosthetics [5, 6]. This chapter aims to look beyond the innovation of materials and microprocessor-controlled prosthetics which has been the center of attention in the previous reviews. It focuses on the challenges in the life of an amputee along with the technological innovations. It illustrates how prosthetics today can go beyond the means of mobility and significantly improve the quality of life of amputees.

2. Methodology

This chapter analyzes literature from 2005 to early 2025 obtained from PubMed, Scopus, IEEE Xplore, and Google Scholar. “Biomechanics”, “prosthetic devices”, “gait abnormalities”, “rehabilitation”, and “amputee” “challenges in prosthetic design” were included in the search to ensure that the most relevant results were included. This approach sought to identify gaps in innovation as well as the challenges that restrain the advancement of research and development in prosthetic technologies.

2.1 Study selection

This chapter focuses on the lower-limb prosthetic devices which aid in the correction of abnormal gait due to lower-limb amputation. The challenges experienced in the current prosthetic limbs, particularly the lack of alignment, energy efficiency, and socket fit, were the main concern of this chapter. These aspects are vital and need to be considered since they define the effectiveness of prosthetics, their comfort, and usability. These issues need to be solved not only in order to develop and evolve the technology itself, but also in order to make the lives of amputees better.

This chapter also concentrated on innovative solutions made to address these challenges, including the microprocessor-controlled joints, energy-storing prosthetic feet, and prosthetics powered by AI. The efficiency of prosthetics can be greatly enhanced by using advanced artificial intelligence technology, mainly in the case of serious limb

amputations. Combining these technologies with the prosthetics can enhance the mobility and comfort of the users. In addition, studies that monitored biomechanical parameters like step length, joint angles, and muscle energy expenditure were also included because they impact the efficiency of walking with prosthetics.

To preserve focus on the advanced lower-limb prosthetic technologies, studies that focused on upper-limb prosthetics and those with weaker methodologies were removed. Also, implant-based prosthetics that directly attach to the bone were not covered in this chapter, as these solutions are not commonly used for limb loss or amputation.

2.2 Data extraction

After gathering studies, the key data were evaluated for both the acceleration and the barriers in the prosthetic technology. The barriers pertaining to alignment, energy expenditure, and socket fitting were examined in detail as they pose the greatest challenges to the function, comfort, and usability of modern prosthetic devices. These limitations were systematically analyzed to demonstrate where prosthetics fail to meet users' expectations and where innovation is needed in these devices.

With these challenges set, focus shifted to the attempts being made toward improving prosthetic functioning. Significant improvements like the AI-powered feedback systems and adaptive prosthetics were evaluated for their ability to improve symmetry of gait, postural stability, and energy expenditure, which are necessary for walking in a more natural manner. Also examined were microprocessor-controlled joints and energy-returning prosthetic feet, even though their cost and maintenance constraints limit their use.

Moreover, this chapter examined the constraints regarding accessibility, especially in under-resourced environments, where sophisticated prosthetic technologies may not be possible. These considerations were taken to balance the strengths and weaknesses of prosthetic technologies.

2.3 Reflections on the methodology

This chapter combines the findings of existing prosthetic technologies with those of biomechanics to evaluate the progress and shortcomings of prosthetic devices. The methodology used here offers balance in that it considers the more advanced technologies, such as feedback systems and adaptive prosthetics, while also addressing the more prevalent issues of alignment, energy efficiency, and socket fitting that hamper the devices' performance and prosthetic user friendliness.

However, while this chapter presents valuable insights, certain limitations must be acknowledged. The use of published studies, for example, poses a risk of selection bias because not every study includes longitudinal user assessments in the low-resource setting. In addition, despite this chapter's thoroughness, it is constrained by a lack of literature on more recent technologies and understudied areas.

Moreover, concentrating solely on lower-limb prosthetics may have deepened the focus of findings, but the decision to omit upper-limb prosthetic studies likely broadened the scope of findings. In addition, the practical challenges that amputees encounter in their daily lives with prosthetic devices could be analyzed more intensively in the methodology in terms of accumulating user and clinician feedback and conducting more clinical trials. The methodology applied in the present chapter is shown in **Figure 1** which reflects the major steps taken in the process of analyzing the lower-limb prosthetics challenges and technologies.

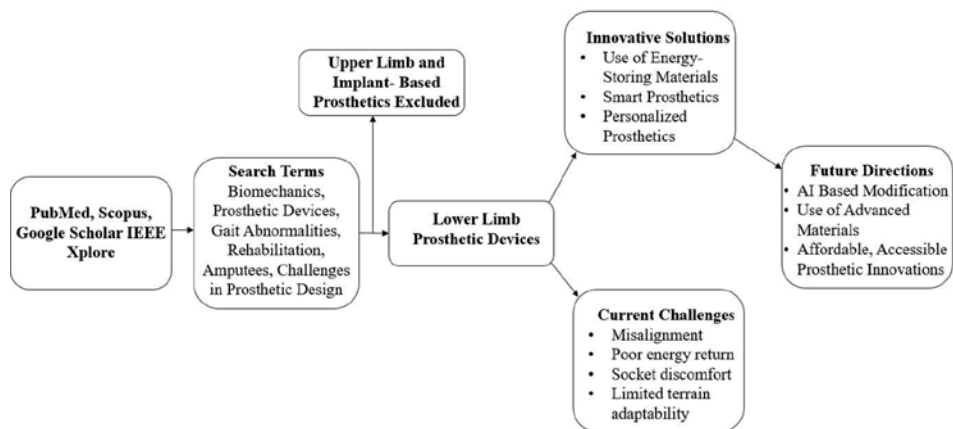


Figure 1.
Methodology for analyzing challenges and technologies in lower- limb prosthetics.

3. Biomechanics of gait

Gait biomechanics is central to the design of effective prosthetic limbs and to the correction of gait abnormalities. Walking is a multifaceted biomechanical activity that depends on the precise coordination of neuromuscular control, joint movement, and muscle activation to support smooth, energy-efficient motion and stability. This section discusses the principal phases of the gait cycle, the modifications observed in the presence of abnormalities, and the biomechanical factors most relevant to prosthetic design.

3.1 Phases of gait

The human gait cycle is composed of two principal phases: the stance phase and the swing phase. Stance phase constitutes approximately 60% of the cycle, beginning with initial foot contact on the ground and encompassing initial contact, loading response, midstance, and terminal stance. At this phase, the limb carries body weight, ground reaction forces, provides balance, and forward propulsion [7].

The swing phase takes the remaining 40% of the gait cycle, and it is divided into pre-swing, initial swing, mid-swing, and terminal swing. It is the phase of elevation of the foot and extension of the limb in preparation for the next step, which needs joint coordination and sufficient clearance of the foot [7]. The development of effective prosthetic limbs aims to closely replicate natural walking movements to the greatest extent possible, in order to achieve an efficient and smooth gait.

Table 1 presents a comparison between the stance and swing phases, highlighting their key characteristics and functional roles in human gait.

Smooth transition between gait phases is critical to sustaining an efficient gait. Disturbances arising from musculoskeletal or neurological impairments may result in pathological gait patterns, increased energy demands, and a heightened risk of falls. A comprehensive understanding of these stages is therefore fundamental for designing prosthetic limbs that replicate natural movement while improving user stability and comfort [7]. **Figure 2** depicts the normal gait cycle, which consists of two principal phases: stance and swing.

No	Feature	Stance phase	Swing phase
01	Ground Contact	Foot in contact with the ground	Foot is off the ground
02	Function	Weight-bearing, stability, propulsion	Limb advancement, Foot clearance
03	Duration in Gait Cycle	~60%	~40%
04	Key Components	Heel strike, midstance, Push-off	Initial, mid, and terminal swing
05	Prosthetic Considerations	Shock absorption, weight distribution, alignment	Lightweight design, smooth motion control

Table 1.
Comparison of stance and swing phases of the gait cycle. A summary of the function in two key phases of the human gait, used in prosthetic design and gait analysis.

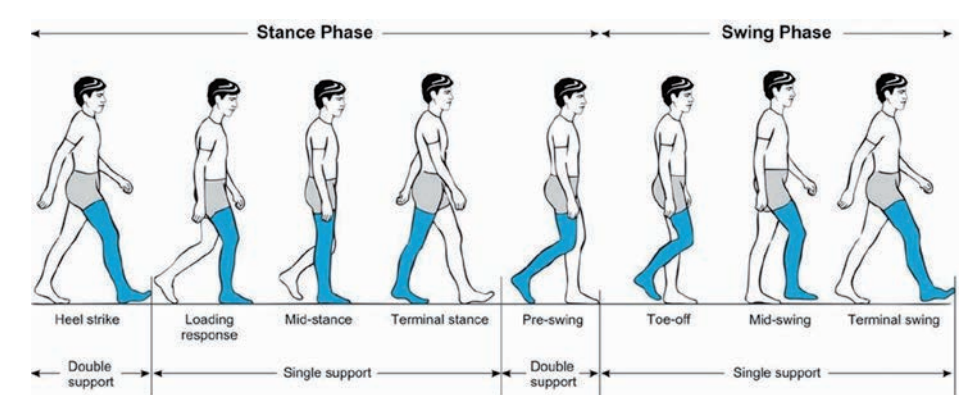


Figure 2.
Illustration of the complete normal gait cycle [8]. Reprinted from Gait disorders in adults and the elderly by Ref [8]. ©The Author(s) 2016. This article is available at SpringerLink with Open Access. Licensed under Creative Commons Attribution 4.0 International License (CC BY 4.0).

When the biomechanical rules are applied in the development of the prosthetics, the users are able to have better mobility. At the same time, it makes their walking less taxing on their minds as well as increases their confidence when walking. Recent studies aim at enhancing these movements to further the processes of developing prosthetic devices that produce effective natural strides for the users.

A smooth transition between these phases is required to make efficacious locomotion and energy conservation. The alterations in timing, organization, or mobility between these systems may lead to gait abnormalities, energy waste, and a greater possibility of falls.

3.2 Altered biomechanics in gait abnormalities due to amputation

Lower-limb amputation results in profound biomechanical alterations that disrupt gait as well as posture. The loss of a limb results in the body attempting to compensate and achieve balance which leads to asymmetric gait and inefficient movements. These changes in movement mechanics dangerously overload the functional limb and the joints [9].

3.2.1 Gait changes post amputation

The changes in biomechanics following an amputation disrupt the balance of the body, leading to an asymmetric gait that affects the symmetry of both the stance and swing phases, as the two limbs can no longer work together. Hence, amputee individuals tend to perform the following compensatory movements:

Hip hiking: While attempting to gain clearance for the prosthetic limb, the user may lift the hip on the side of the prosthetic limb during the swing phase. This leads to a reduced step length or increased limping as well as increased energy exhaustion while attempting to walk. Although this movement aids in foot clearance, it causes discomfort while walking and uneven strain on the pelvic girdle [10].

Circumduction: In this form of walking, the prosthetic leg is moved in a circular motion to prevent the foot from dragging. The further the foot is from the body during the movement, the greater the effort the body is required to spend, which in turn, makes walking tiring and difficult. In addition, the circumduction gait pattern can lead to hip and knee joint stress and over time may lead to joint degeneration [11].

Vaulting: The prosthetic may encourage the user to lift their body up to move the body to a different place. The intact limb is crucial in moving the user, making the leg take a lot of stress. Additionally, vaulting is a very energy and calf intensive movement which causes the user to get easily fatigued over extended distances [9].

To some degree, these movement patterns are problematic, and the need for efficient gait is highly undermined. The result is limb inefficiency which also leads to increased strain, pain, and joint problems in the limb which is not injured.

3.2.2 The impact of limb loss on joint mechanics

The loss of a limb lowers one's movement efficiency and gait biomechanics for the entire leg. It also now involves the pelvis and the spine along with other musculoskeletal components which now needs to adjust to the new movement dynamics of the body because a limb is missing. This leads to the center of mass and the center of gravity undergoing significant shifts which is vital for maintaining the upright balance of the body. It is also vital for maintaining balance, posture, and stability. Because of this, there is a higher chance of biomechanical instability which increases the risk of falling and also increases strain on the remaining body parts, joints, and also on the hips, knees, and lower back [12].

Additionally, below the knee amputees, also known as transtibial amputees, are more efficient than above the knee amputees, such as transfemoral amputees. This is because above the knee amputees have to exert more effort during gait for compensatory adequacy which requires greater center of gravity regulation. This is more than what below the knee amputees are used to [13].

3.2.3 Postural and functional changes

After the unilateral lower-limb amputation, maintaining optimal postural alignment becomes increasingly challenging. Common accompanying movements such as hip hiking, circumduction, and vaulting disrupt the neutral position of the pelvis

and spine. These habitual movements over time lead to chronic postural imbalance and asymmetry. This, in turn, exacerbates gait and balance control. These persistent deviations introduce mechanical stress, abnormal chronic forces, and disrupt the mechanical environment of the musculoskeletal system, particularly of the intact limb, which directly bears the brunt of the weight amplification when walking [14].

Moreover, the unilateral limb amputation prosthetic usage accelerates the degenerative changes of joints in the unaffected limb. This is primarily due to the excessive biomechanical alignment imbalance resulting from the unadapted prosthesis. The chronic compensatory effort from the unaffected limb joints can contribute to further joint problems, loss of mobility, and diminished quality of life for amputated individuals [15].

4. Challenges in current prosthetic designs

Recent advances in prosthetic technology have made significant progress in mimicking human movement. However, existing prosthetic limbs still cannot replicate the biomechanics of natural walking closely enough. These devices often lack the flexibility required for smooth, natural movement, which leads to increased physical and mental strain for users. This section examines key challenges in prosthetic design, such as joint misalignment, long-term musculoskeletal risks, and postural issues. It also highlights the importance of achieving a comfortable socket fit and helping users adjust psychologically to their prosthetic limbs.

4.1 Misalignment and joint stress

Prosthetic malalignment is a common issue among amputees, contributing significantly to abnormal gait, poor posture, and long-term joint damage. Misalignment causes uneven walking patterns and misaligned posture, disrupting the natural rhythm of movement and increasing pressure on the knee, hip, and lower back joints. Alignment techniques, such as bench, static, and dynamic methods, often struggle to accommodate the individual needs and unique body structures of users. While these methods provide partial solutions, they do not fully account for the dynamic nature of human movement, which can lead to poor posture, overloaded joints, and secondary movements that limit functional mobility [16, 17].

Bench alignment fixes the prosthetic device in a static position. It does not account for the user's dynamic movements. This approach oversimplifies the complexity of real-world use. The technique presupposes that a prosthetic limb would be able to do equally good either in a user standing or in walking, which leads to the regular misalignment when one is in motion. Static alignment is concerned with presetting the socket relative to when the user is standing in a relatively fixed posture. It, however, fails to take into consideration dynamic interactions of walking that may result into misalignment when it comes to movement, and hence gait and posture [18, 19].

Dynamic alignment, however, varies the prosthetic in relation to the movement of the user and seeks to optimize the mechanical interaction between the limb and prosthesis in the process of walking. Dynamic alignment can improve walking by adjusting the prosthetic in response to the user's movement, but its effectiveness is limited by the inconsistency of adjustments over time, as the user's body changes. Irregular recalibration may lead to discomfort and joint overload, as well as faster wear on the residual and intact limbs, resulting in lifelong health issues [20].

4.1.1 Impact on adjacent joints

Poor fitting of the prosthetic device does not only compromise the residual limb but also places excessive stress on the articulating joints such as hip, knee, and lower back. An incorrect alignment of prosthetics means that the rest of the body will modify the movement patterns to the new and uncomfortable position, becoming unbalanced in load and adding more pressure to the other limb. Such compensatory mechanisms as pelvis shift and trunk tilt lead to the asymmetrical distribution of the weight, which, eventually, leads to primary injuries (joint overstress) and secondary injuries [21].

Misaligned prosthetics distort the transmission of forces to the residual limb via the socket, frequently causing joint contractures and impairing the general comfort and performance of the prosthesis [22]. This repetitive strain contributes greatly to the chances of having degenerative joint disorders like osteoarthritis, in the intact limb. Such malalignment in the long-run may greatly restrict mobility and lead to a loss of overall functional health [23–25].

4.1.2 Long-term effects: Risk of arthritis and degenerative conditions

Misalignment has potential long-term effects that may even go beyond temporary discomfort and translate into degenerative conditions. A misaligned prosthetic device will cause an imbalanced gait that will unduly strain the joints, especially the hip, knee, and the lower back. Such aberration promotes faster wear and tear, and thus, more chances of contracting arthritis and arthritic joint diseases in the intact and residual limb [26].

Specifically, mismatch early in the life cycle of prosthesis may result in premature wear of joint cartilage, not just the hip and knee. The long-term issue of joint health might cause a new challenge of mobility that may limit a person to carry out day-to-day activities and ultimately compromise the overall quality of life of amputees. Studies have demonstrated that the nonalignment places the contralateral limb under a lot of stress which will lead to the development of osteoarthritis and other degenerative diseases as individuals tend to counterbalance the body through the prosthetic [15].

4.1.3 Alignment challenges: Difficulty maintaining proper posture

The strongest effect of the misalignment should be inability to keep proper posture, and this may be an influential impact on balancing and locomotion. Proper prosthetic alignment plays a crucial role in maintaining balance by preventing excessive rotation of the socket around the residual limb. Alterations in prosthetic alignments, even 2°, 4°, or 6° angular deviations, or in 5 mm, 10 mm, 15 mm along the translation axis, systematically impact the socket reaction moments and may make it hard to maintain balance and coordination in a user when walking. Such mismatch causes compensatory motion and thus excessive trunk anterior or lateral flexion that results in a high likelihood of falls and distorts the general postural stability [27, 28].

Factors such as including sensor-integrating prostheses and real-time feedback system may reduce these difficulties by making sure that the prostheses are aligned more precisely in everyday activities and minimize having to manually adjust it. Minimized recalibration and long-term usability may greatly increase comfort of use and hindering possible posture misalignments [28, 29].

The difficulty of having the right posture has been increased in the presence of inconsistent or poor alignment. There is discomfort among the users, resulting in poor confidence of walking and use of secondary movements (compensatory mechanisms),

straining other muscles. Inadequate posture and dynamic balancing also restrict the functional capacity and expose to more secondary musculoskeletal injuries [30].

4.2 Limited energy efficiency and propulsion

One of the most persistent biomechanical limitations in conventional prosthetic limbs is the inefficient management of energy during gait. Unlike biological limbs that naturally store and release elastic energy, prosthetic limbs often lack the dynamic response required for fluid, energy-efficient walking. This inefficiency increases the user's metabolic cost, reduces gait symmetry, and contributes to fatigue—especially during prolonged or variable-terrain ambulation [27, 31, 32].

4.2.1 Reduced propulsion during walking

A key issue in prosthetic gait is the absence of active push-off capability. Most conventional prosthetic feet and ankles are passive, limiting forward propulsion and creating an asymmetry between the prosthetic and intact limb. As a result, users often compensate by shifting greater load to the intact limb, which can lead to overuse injuries and reduced walking efficiency [33, 34]. Microprocessor-controlled knees and ankles have shown some improvements, but challenges persist, especially for high-mobility users such as athletes and active adults [32, 35].

4.2.2 Energy return limitations: Lack of natural gait dynamics

Although energy-storing-and-return (ESR) feet have improved prosthetic performance, they still fall short of replicating the natural responsiveness of biological limbs. These devices may return energy too early or too late in the gait cycle, failing to provide the seamless transition necessary for dynamic walking—particularly on uneven terrain or during rapid gait changes [31, 36, 37]. Advanced ESR technologies and powered joints continue to be explored to bridge this gap, with promising but still evolving results [32, 38].

4.2.3 Fatigue concerns: Increased effort for mobility

The prosthetics lack good energy storage and return features that make the user tire faster than a normal person. Research shows that people with transtibial amputation use between 10 and 30% more metabolic energy than able-bodied individuals. This more intense energy consumption results in more muscular work, in the fit limb and the available muscles of the functional limb [39].

Users may also feel tired even after a short time of walking as they have to undergo some additional physical activities. Prosthetic users have to engage in not only physical workload but also additional psychological stress when walking [40]. The use of prosthetics makes walking a challenging process that demands a lot of energy since the process of walking has become an activity that demands too much mental attention. The solution to the problem can be resolved by introducing prosthetic devices with better functions of converting energy to work efficiently to offer the users more freedom and less fatigue.

4.3 Discomfort and adaptability issues

The factors that affect long-term compliance of prosthetic use and user satisfaction are comfort and adaptability. Although the technology has advanced

considerably, most users of prosthetics still deal with a number of challenges, such as an ill-fitting socket, the inability to navigate different types of terrain, and, ultimately, a lack of psychological confidence in their device. Besides resulting in a decrease in functional outcomes, these challenges also lead to the decreased quality of life of many amputees [28].

4.3.1 Socket fit problems: Skin irritation and pressure points

Poor socket fit is one of the most common complaints of prosthesis users and may result in pressure points, tissue irritation, and appearing of ulcers or infections [41]. The size of the residual limb changes regularly due to swelling, muscle loss, or weight changes. This means that the prosthesis must be adjusted often to make sure it stays comfortable and secure [28, 42]. In response, newer models feature the availability of smart sockets featuring adjustable interfaces, the usage of gel liners, and also vacuum suspension devices although their high cost and limited availability remain major barriers.

Scientific specialists obtain a special prosthetic socket with the combination of gel liners with a vacuum system, and they perform the design of adaptively shaped sockets. Contemporary research projects invent a flexible feature of the socket layout that is able to respond to the changes occurring in the volume size. **Figure 3** presents an updated version of the latest socket model for a lower-limb prosthesis. The innovations target two objectives which include hotspot pressure reduction and user comfort

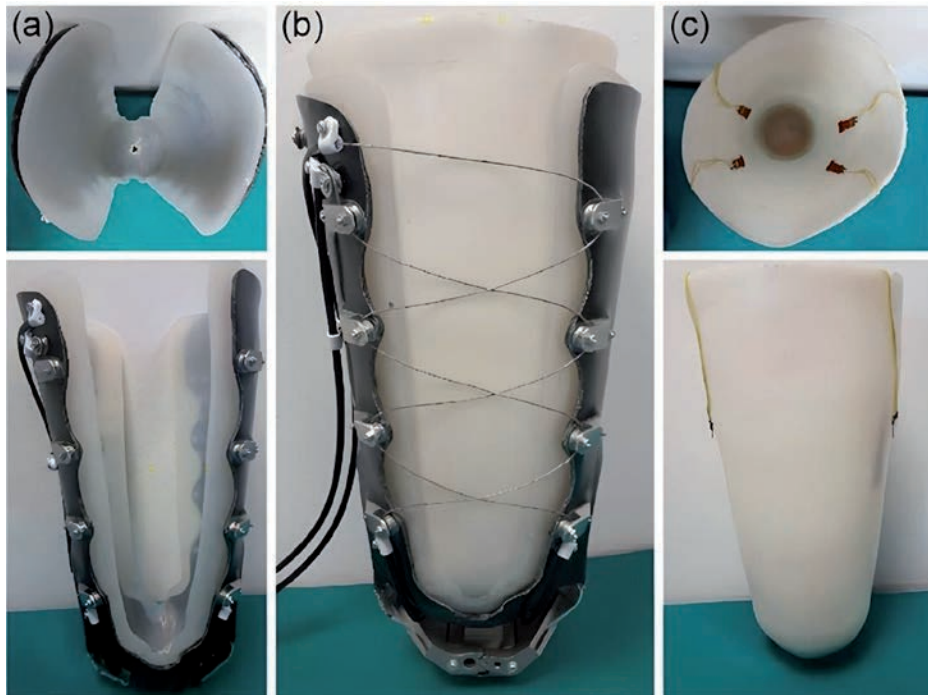


Figure 3. (a) Outer rigid socket (black) and inner flexible socket (white); (b) Final adjustable socket system featuring a cable-driven mechanism; (c) Silicone prosthetic liner embedded with four FSR sensors [42]. Reprinted from Smart Transfemoral Prosthetic Socket with Motorized Cable-Driven System by Ref. [42] © 2025 The Author(s). Advanced Intelligent Systems published by Wiley-VCH GmbH. This is an open access article under the terms of the Creative Commons Attribution License.

improvement. Users across the world encounter difficulties in accessing affordable advanced sockets despite recent technological developments [41].

4.3.2 Lack of adaptability: Challenges with varied terrains and activities

Although these prosthetic devices achieve high performance in level-ground walking conditions, overall performance deteriorates in uneven terrain or high-demand activities such as stair climbing, slope navigation, or rapid directional changes. This confines users' movements and autonomy in real-world conditions. These types of advanced technologies which have been designed to increase stability and functionalities for the user, such as microprocessor-controlled knees and terrain adaptive feet, still remain scarce in low-resource settings due to their high cost and required maintenance [43, 44].

4.3.3 Psychological impact: Reduced user confidence and satisfaction

The body is unable to ignore the physical discomfort, instability, and difficulties with prosthetic use. These ongoing issues often evolve into psychological strain, affecting the user's emotional well-being. Others experience a loss of confidence, a lack of desire to communicate with others, and anxiety caused by prosthesis use, especially when the discomfort arises and impedes day-to-day life [45, 46]. Such emotional burdens can potentially diminish rehabilitation results and impede regular prosthetic utilization. On the other hand, the user of ergonomically designed and functionally responsive prosthetics commonly shows better psychosocial adjustment and satisfaction.

4.4 Key metrics for prosthetic challenges

It is vital to measure accurately step length, cadence, velocity, joint angles, limb trajectories, and ground reaction forces to analyze the success or failure of prosthetics. Measuring ground reaction forces is equally important. Collectively, these metrics examine the relative effectiveness of the prosthetic limb dynamic symmetry.

4.4.1 Spatiotemporal metrics: Step length, cadence, and velocity challenges

Prosthesis users and designers alike have come up with numerous ways to measure the effectiveness of a prosthetic limb, step length, cadence, and velocity defined by speed and symmetry to make the evaluation more user-friendly.

4.4.1.1 Design challenges

- **Step length:** Step length refers to the distance between successive footfalls. Users often struggle to achieve natural step length because of socket misalignment. Prosthetic alignment or gait matching is a burgeoning field of exploration. Inability to match gait of the user due to failure or absence of adjustment will usually lead to loss of stride and gait asymmetry. The development of flexible or adjustable sockets has the potential to mitigate these issues by enabling a better fit of the prosthetic in line with the length of the limbs and walking pattern of the user [36].

- **Cadence:** Cadence means the number of steps taken per minute. Low prosthetic energy return reduces the cadence of movement and makes it harder to maintain speed. This problem results from the inadequate push-off power provided by many prosthetic feet and joints. Energy storage feet or powered prostheses have the potential to augment cadence through push-off forces upon toe-off and resemble preferred gait [33].
- **Velocity:** Velocity refers to the overall walking speed of the user. Lower-limb amputees tend to walk more slowly as compared to nonamputees. This slower pace is largely a result of insufficient prosthetic propulsion and inefficient gait patterns induced by the prosthetic. A primary concern for the prosthetic industry is increasing walking speed, enhancing energy return while limiting hip hiking or vaulting [47].

4.4.2 Kinematic metrics: Joint angles and limb trajectory challenges

Joint angles and limb trajectories are key parameters measured during the gait cycle of individuals using a prosthetic limb. These measurements provide insight into how well the prosthetic facilitates natural movement patterns of the human musculoskeletal system.

4.4.2.1 Design challenges

- **Joint angles:** Joint angles refer to the range of motion in major joints such as the knee and hip during walking. Prosthetic devices with fixed knees or ankles tend to restrict joint movement and increase the spread of angles. For instance, prosthetic knees may not actively flex or extend during the gait cycle. This limitation makes it harder for users to achieve a natural gait. Incorporating microprocessor-controlled knees and ankles can provide a greater range of motion, enhancing responsiveness to different walking speeds and changes in terrain [48, 49].
- **Limb trajectory:** Limb trajectory means the path taken by the prosthetic limb during walking. Prosthetic limbs should ideally manage motion in all three anatomical planes, just like a natural gait cycle, but current prosthetics are unable to achieve this. Also, a majority of prosthetic feet do not have the motions of natural foot supination and pronation, which contributes to the previously mentioned unnatural limb trajectories. More advanced prosthetic feet with the ability to adapt to different walking surfaces during walking may provide the required range of motion during supination and pronation, thereby improving limb trajectories, which in turn should reduce body strain and improve walking efficiency [50, 51].

4.4.3 Kinetic metrics: Ground reaction forces and energy transfer challenges

Ground reaction forces (GRF) and energy transfer are two key kinetic measures used to understand how a prosthetic foot interacts with the ground. These metrics play a crucial role in assessing the stability and overall functionality of prosthetic devices during walking.

- **Ground reaction forces:** Ground reaction forces (GRF) are the forces exerted by the ground on the prosthetic foot during contact. Often, prosthetic devices fail to

transfer and absorb ground reaction forces and then transfer them back, causing too much shock and more fatigue in the healthy limb. Without proper shock absorption and energy return, prosthetic limbs can be uncomfortable and may even lead to long-term joint damage. The problem described may be alleviated by prosthetic feet which incorporate improved shock-absorbing materials or energy-storing features [52, 53].

- Energy transfer: Effective energy transfer from the ground to the prosthetic limb during walking is critical for propulsion and stability. Many prosthetic designs are not capable of efficient energy transfer, leading to an increase in the metabolic cost and fatigue. Reduced energy demands during walking can be achieved with prosthetic designs which store energy at the foot strike and return it at toe-off [31, 37].

4.5 Summary of design limitations

The technological sophistication of modern prosthetics has added features and benefits but has not overcome some of the basic constraints of the current designs. These are lack of ideal alignment, energy wastage, and poor fit of the socket leading to user discomfort and poor adaptability on different terrains. All these combined decrease the efficacy, comfortability, and satisfaction of the prosthetic limbs by the user. **Table 2** summarizes the most important limitations that users of contemporary prosthetic systems are exposed to.

No	Challenge	Impact
01	Misalignment	Joint stress, postural imbalance
02	Poor energy return	High fatigue, reduced efficiency
03	Socket discomfort	Skin irritation, poor user satisfaction
04	Limited terrain adaptability	Restricted mobility, reduced confidence
05	Key metrics for prosthetic challenges (spatiotemporal, kinematic, and kinetic)	Gait asymmetry, reduced walking speed, high fatigue, inefficient joint motion, unnatural limb trajectories, increased metabolic cost, and stress on the intact limb

Table 2.
Key challenges in existing prosthetic designs. The table lists the major functional and biomechanical constraints of traditional lower-limb prosthetic systems.

5. Innovative solutions in prosthetic design

The field of prosthetic design has seen remarkable evolution from simple mechanical limbs to sophisticated, biomechanically intelligent systems. Beyond merely restoring mobility, today’s research emphasizes enhancing biomechanical efficiency, improving energy return, and maximizing comfort and adaptability. Modern prosthetics aim to recreate the dynamic interaction between limbs and terrain while addressing key challenges like user fatigue and uneven gait. This section deals with state-of-the-art technologies and materials designed to enhance user outcomes, particularly in amputees with severe gait anomalies.

5.1 Energy-storing materials for motion

One of the best inventions in the field of prosthetics concerns the incorporation of substances that simulate the springy behavior of tendons and muscles. These systems of mechanical energy storage and release make use of mechanical energy to store and release during walking, therefore reducing the amount of energy necessary to be expended by the user and enhancing efficiency during the gait process [54].

5.1.1 Advanced materials with high energy return

Prosthetic feet contain materials such as carbon fiber (CF) composites, polyurethane elastomers, and thermoplastic resins which are well-adapted because of desirable mechanical characteristics. Carbon fiber (CF) is identified by its strength, flexibility, and resistance to stresses and strains and is thus used to create dynamic reaction feet. It is also lightweight, thus resulting in less swing effort, giving an responsive gait [55]. Researchers at present investigate shape-memory alloys and nanocomposites with the purpose of enhancing prosthetic devices through improved energy storage systems. Adaptive prosthetic components become possible with shape-memory alloys because these materials return to their original form after they undergo deformations. Scientists are studying nanocomposite materials that link polymers with graphene-sized fillers because these materials demonstrate characteristics that could boost prosthetic limb function [56].

In addition to improving walking efficiency, the goal of these advanced materials is to recreate the push-off feeling of biological legs in the prosthetics, making them mimic natural movement as closely as possible. It is, however, difficult to fully attain this effect using the current prosthetic technology. The energy return has been significantly improved through recent research of athletic prosthetic feet with composite materials, including polymethyl methacrylate resin (PMMA), reinforced by fibers, such as ultrahigh molecular weight polyethylene (UHMWPE), Perlon, carbon fiber, and glass fiber. Results demonstrate that the carbon fiber layers added to UHMWPE enhanced deformation by 26% developing better storage and release of energy. In addition, this noticed that more the layers, the more the improvement of 31% for carbon fiber and 32% in case of glass fiber that helped increase energy returns and overall performance [57]. Specifically, recent nanocomposites have excellent shock absorption and vibration damping aspects that may be of great relevance to active users involved in sports or frequent walkers. The user becomes less fatigued since the limb is assisting in storing energy instead of being in a passive state. This eventually affects not only the mobility but also the quality of life, as individuals become capable of carrying out routine or pleasure activities with additional confidence and comfort [58].

Although carbon fiber composites are both strong and lightweight, they can become brittle after repeated loading cycles, particularly during high-impact activities like running or jumping. This brittleness can lead to the development of micro fractures over time, compromising the long-term function and safety of the prosthetic limb. This is a major concern for active users or athletes who constantly subject their prostheses to intense, repetitive stress [59, 60]. Additionally, the manufacturing process for carbon fiber is costly and complex, making it difficult to customize these parts to fit the unique anatomy of an individual. As a result, high-quality prosthetics are not easily accessible, especially for lower-income or rural communities, where cost and availability pose significant barriers [61, 62].

5.1.2 Adaptive response to different activity levels

Real-world usability has been improved due to the development of activity-responsive prosthetic feet. These have embedded sensors and actuators which monitor ground reaction forces, and the gait phase allows dynamically variable stiffness control [63]. Consequently, the users feel more balanced and experience less cognitive strain as they move between the stages of walking, running, or climbing stairs. Such an attribute is specifically useful to active users and people working in unfavorable surroundings [64]. They lead to more natural transitions and reduce the risk of falling due to dynamic adjustment in real time to the terrain and pattern of walking or movement of the individual. Moreover, improved accuracy of sensors and responsiveness of actuators have enhanced the sensorimotor response and overall usability of the prosthesis, particularly during complex tasks such as walking on uneven surfaces or climbing stairs [65].

Adaptive systems provide a more natural sense of movement and demand less mental effort, since users are not required to consciously plan every step. Their intelligent responsiveness enhances both safety and convenience when moving through complex settings such as crowded streets, uneven surfaces, or stairways [66, 67]. Many users report feeling a stronger sense of autonomy and spontaneity in daily activities, which contributes to greater self-confidence and an enriched social experience. Adjustable prosthetic feet further reduce self-consciousness, allowing users to feel socially at ease and empowering them to engage more freely with others [68].

Sophisticated prosthetic systems using sensors and powered systems are prone to consume high level of energy, which would lead to frequent charging or purchase of new batteries. This is not always convenient or even viable to the users, more so in cases where the availability of electricity is not practical [69]. Secondly, sensor-based control systems sometimes fail to properly interpret the terrain changes or fluctuations in the intentions of users, resulting in unexpected stiffness changes that can cause a degree of discomfort, instability, or even loss of balance in any switching of movement. The technicalities related to such technologies further contribute to the high cost and load of maintenance, and hence such a prosthetic solution is unlikely to be feasible in poor or low-resource locations, where the technical support system and infrastructure are minimal [70].

5.1.3 Integration of kinetic energy harvesting

One new area of prosthetic development is the use of kinetic energy harvesting to capture biomechanical energy while walking to run onboard electronics. This comprises gait monitors, microprocessor knees, and wireless communications systems [38]. Other technologies like piezoelectric elements and electromagnetic harvesters built into artificial limbs can dramatically increase the autonomy of devices to the point that constant charging or battery replacement is no longer an issue. Initial studies demonstrate that the long-term sustainability of smart prosthetic devices may be enhanced successfully. Such advancements increase the user's mobility and simultaneously lessen their daily reliance on external chargers. Users are less concerned about the ability to charge devices, and with greater movement reliability, their performance while in motion and mobility increases. Thus, the comfort and confidence while on the move increase. For many, it simply means being able to go about their day without the nagging thought of whether their limb can keep up [71].

Further, kinetic energy harvesting does not create a burden on the user to keep track of the batteries at all times and ensures a smooth, hassle-free experience when on extended trips. It also fits with eco-conscious audiences in converting daily movement to renewable power and minimized the amount of electronic waste and energy used [72]. To those who travel or work in areas where there is no access to chargers, this technology would almost guarantee the people that their prosthesis would not be plugged in, yet it could still work. The set of features results in an effect of independence and peace of mind being created that provide the prosthesis constant support to the user [73].

Energy harvesting technologies in prosthetics will produce power as the user moves, although the system in use is expected to have low electrical power production, usually too little of it to power the prosthetic [38, 74]. In this case, this output often does not match the energy requirement of the critical microprocessor controls or active feedback loops embedded in the modern prosthetic such as microprocessor-controlled legs. This integration of energy harvesters may swell the size and weight of the prosthesis which may not provide a comfortable fit to the user or cause a change in the natural gait. In addition, their stability and resilience in the long run in severe conditions of the real world are not yet reliably demonstrated which limit their mass adoption [74].

5.2 Smart prosthetics with real-time feedback

The development of intelligent prosthetic systems marks a new era in rehabilitation engineering, where prosthetic limbs become fully integrated into the body, rather than simply serving as passive devices. Modern prostheses are now equipped with real-time feedback, enabling dynamic adjustments during movement, which significantly enhances gait quality, comfort, and safety. These advanced systems employ sensors, actuators, and microcontrollers to assess biomechanical performance and make autonomous adjustments. As a result, users experience improved stability, more natural coordination of the limbs, and a reduction in compensatory behavior [75].

These devices employ a synergy of sensors and algorithms that detect surface types, walking patterns, fatigue levels, and gait abnormalities. Touch-based feedback, audio-visual cues, and neuromuscular stimulation help guide corrective movements, thus reducing the strain on the sound limb and lowering metabolic energy costs. Real-time adjustments improve prosthesis responsiveness to varied terrains and activities, enabling intuitive interaction and boosting overall user satisfaction [76].

5.2.1 Sensory feedback mechanisms

Sensory feedback is essential for proprioceptive awareness in prosthetic users, allowing for better control over limb positioning and motion. Advanced systems integrate tactile sensors with neural and myoelectric interfaces to restore sensation by transmitting force and sensory information to the residual limb. These signals enable the user to interpret contact forces, pressure variations, and ground stiffness, facilitating safer and more coordinated movement [77].

Neuromuscular integration using electrical stimulation and vibrotactile cues has demonstrated promise in reducing phantom limb sensations and improving gait symmetry. Enhanced proprioception through feedback leads to fewer falls, quicker terrain adaptation, and an increased sense of embodiment of the artificial limb. These innovations represent a significant advancement over traditional prostheses, where

lack of feedback often led to over-reliance on visual cues or compensation through upper body movement [78]. By improving mobility and enabling tactile feedback, these technologies help users connect more naturally with their environment. As the technology progresses and becomes more intuitive, it enables users to navigate complex spaces with greater confidence. This leads to a notable improvement in daily mobility and a reduction in physical strain. Furthermore, this advancement in prosthetics brings them closer to the natural biomechanics of the human body, enhancing comfort and minimizing restrictions during use [79].

Nonetheless, sensory feedback processes are an extraordinarily beneficial system; however, they are not without their difficulties. To start with, the adaptation of tactile sensors involves neural or myoelectric interfaces and is quite a cumbersome procedure with the risk of a resulting calibration error. Such minor mistakes may either result in lost or wrong feedback, and it may interfere with the coordination of a user especially in live circumstances [78, 80]. Furthermore, electrical stimulation, although useful in neuromuscular integration, may be uncomfortable to the user especially when the system is not highly tailored toward the needs of the user. Power sources are also very important in sensory systems, and hence, power failure may be encountered whenever the batteries have run out or when they require to be recharged often which can interfere with the experience of the user. Also, though the feedback increases proprioception, it might still need a training period during which the user is able to learn how to utilize the composed sensory input as this can be uncomfortable or confusing in the beginning [81].

5.2.2 Integration with wearable devices or apps

Merging prosthetic systems with wearable technologies and mobile applications is revolutionizing the user experience. Smart prostheses connect with smartphones or smartwatches via Bluetooth, allowing real-time customization of joint stiffness, damping levels, and alignment settings. Step counts, gait cycles, and fatigue indices are tracked through intuitive mobile interfaces, enabling users to make informed choices about their mobility and daily activity patterns [82].

Remote monitoring offers significant advantages to both clinicians and users by reducing unnecessary clinical visits and enabling timely responses to gait data. App-based customization tools also allow users to calibrate their prostheses for specific activities such as walking, running, or cycling, thereby promoting greater independence and activity [83]. Beyond delivering a more personalized experience, these systems permit continuous adjustments, enabling users to adapt their prostheses to diverse terrains and activity levels. This on-demand flexibility enhances comfort and efficiency while minimizing the need for manual intervention. Wearable features further amplify self-monitoring, giving users a more proactive role in managing mobility and overall well-being [84].

However, with all those benefits also come challenges that are associated with the incorporation of wearable technology and apps. Continuous monitoring and data transmission in wearable sensors, if not designed efficiently, can rapidly deplete the battery. While reducing the data sampling rate can help conserve power, it poses a significant risk to the system's ability to detect important biomarkers for tissue health. This directly compromises the clinical relevance and reliability of the collected data [85]. Additionally, the vast number of customization options can be both helpful for personalization and overwhelming for the user. Having so many settings can lead to confusion. The use of mobile apps and frequent updates also come with their own set

of risks: software issues or app malfunctions can disrupt the user experience, particularly when using the prosthesis. Elderly people especially have shown lower efficiency in this technology [86].

5.2.3 Machine learning algorithms for adaptive behavior

The continuous sensory feedback leads to predictive and adaptive control of smart prostheses that are based on machine learning (ML) technologies. The process of these algorithms draws data measured by inertial measurement units (IMUs), pressure sensors, and accelerometers in order to find differences in the terrain, gait pattern, and limb orientation. Depending on the learned patterns, the prosthetic limb is capable of automatically changing joint stiffness, the amount of torque to be delivered, and the time of step taking without involving users [75].

ML-driven systems can be used to predict changes, such as a transition from level ground to stairs, and adjust accordingly in real time. In addition, they identify gait abnormalities that may lead to a fall or musculoskeletal strain to warn the user or make a preventive adjustment [87]. Such predictive intelligence minimizes the cognitive and physical load on the user, increasing both comfort and safety. Such systems will amplify the role of the prosthesis to a smart one that is able to learn and grow with the user. The benefits to the emotional and psychological freedom are among the greatest ones. Once users feel that their prosthetic device is able to realize how they are about to move, they feel more confident and trusting and especially in the congested areas like the streets or the means of transport. This perceived responsiveness is associated with increased independence, higher self-esteem, and lessened social anxiety, and thus, users are able to move in the crowded spaces with greater comfort and confidence [88, 89].

The systems also promote the long-term musculoskeletal well-being by reducing compensation maneuvers (such as leaning sideways or overutilizing the upper body), typical of poor adaptive prosthetics. Due to spreading the effort more effortlessly, they avoid fatigue and joint strain, which means that long walks, daily tasks, or even a minor physical activity are easier to manage and enjoy [90].

The ML-augmented prosthesis transforms into a responsive learning companion that becomes a partner who continues alongside with its user and can support them every day, and not only physically but also in an extremely personal, intimate manner and liberating [91].

Although the systems based on machine learning have achieved a very high level in research settings, they also have certain complications. To start with, the algorithms rely on much relevant data to be functionally trained. When the information gathered by the sensors is inaccurate, either because of a problem in the sensors or due to environmental conditions, inaccurate corrections can be made, which could impact the stability and safety of the user [87, 92]. Additionally, although such systems are improved with time, the initial phases of it may be frustrating to the individuals using it, since a user may have to calibrate the system manually. This is because as the algorithms grow complicated they might need more processing power and kill the battery faster. This would imply that users may be forced to charge their prosthesis frequently particularly when it is actively being used, a situation that can be cumbersome resulting in an inconvenience in the daily routine of the user. Despite reducing cognitive load, there is a learning curve, and not all users will feel comfortable with systems that adapt themselves in real time [93]. Although such ML-based adaptive prosthetic units can greatly improve comfort and independence of users, existing

safety and regulatory requirements have to be met. These systems should adhere to safety standards, like ISO risk management standards and FDA standards in medical devices [94, 95].

5.3 Biomechanics-driven custom designs

Biomechanics-based prosthetic designs use the principles of human movement and musculoskeletal mechanics to create prosthetic devices that work in harmony with the body. These devices are designed to replicate natural limb motion, distribute loads efficiently, and provide both improved function and greater comfort for the user [48, 96]. Individual-tailored designs which are created through analysis of individual movements will provide a correct balance in the distribution of the load, minimizing peak pressure areas and adjusting the limb positions. Specifically, the application of 3D printing results in custom solutions that help to make more bridges between artificial and natural human movement in limbs. Also, biomechanical alignment means that the postural control is more stable, and it decreases energy expenses during ambulation due to less risk of overuse injuries [97, 98].

5.3.1 3D printing for personalized fitting

The latest generation of 3D printing is now being used by prosthetists to create limbs that match the individual anatomy of patients. This technology allows for rapid prototyping of sockets and limb components, which are then produced using thermoplastics and composite materials that are both light and durable, while still providing a customized fit [99]. For people with active lifestyles, these designs are especially useful, since they remain light in weight but strong enough for everyday use. Another advantage is that the process reduces production costs, which makes prosthetic devices more accessible for patients in developing countries or low-income regions [100].

Personalized fabrication also helps reduce irritation of the residual limb and ensures that pressure is spread more evenly across the skin surface. In contrast to traditional labor-intensive methods, 3D scanning and modeling make production faster and more cost-effective, which improves affordability. Looking ahead, advances in 3D printing are expected to push the limits of design, allowing prosthetic devices to adapt more closely to the needs of each user by offering greater mobility and improved self-confidence. These personalized designs can be refined over time with feedback from gait analysis and direct patient input, creating a cyclical, user-centered design process [101, 102].

There are some limitations to 3D printing prosthetics. The initial investment to acquire a 3D printer and purchase specialized materials is usually too high for clinics located in low-resource regions [103]. Moreover, regarding the longevity of 3D-printed prosthetics, thermoplastic materials are not likely to be a good long-term option, as they tend to be much weaker than traditional materials for wear and tear over time, in the context of strenuous activities. Alignment problems in 3D-printed lower-limb prosthetic sockets can arise from plastic deformation caused by repeated loading. Digital image correlation (DIC) measurements on laser-sintered PA12 (Polyamide 12) transtibial sockets have revealed localized plastic deformation, particularly in high-strain regions such as pin-lock interfaces, after one million gait cycles [104, 105].

5.3.2 Dynamic load and stress analysis

Regulating the mechanical load is essential for the development of long-lasting and bio-interface-compatible prosthetics. Dynamic load and stress analysis allows designers to examine the different forces acting on a prosthesis during walking, such as ground reaction forces, inertial effects on the limb, and joint torques. This approach helps ensure both the mechanical reliability of prosthetic devices and user comfort during prolonged wear [16]. Computational modeling tools, such as finite element analysis (FEA), enable precise mapping of stress distribution and support structural optimization. This is particularly important for pediatric and high-activity users, where growth and variability in gait patterns demand greater strength. Such simulations contribute to advancing prosthetic design by improving resistance to fatigue and enhancing postural stability [106].

Additionally, by accurately modeling the stresses and loads on a prosthetic limb, designers can create more durable and resilient devices that better mimic natural limb behavior, reducing the risk of failure over time. This approach also allows for customization, where the prosthetic can be optimized for specific tasks or conditions, such as increased load during sports or varied terrains [107]. Furthermore, dynamic load analysis helps to enhance overall prosthetic performance by reducing unnecessary stress on the user's body, promoting smoother movement and improving the long-term health of the intact limb. As a result, this technology not only improves mobility but also provides greater comfort, helping users feel more confident in their prosthetics during daily activities [108].

Also, the use of the technology presupposes that the user can sit and remain stable. Nevertheless, the changes in bodies of users tend to occur with the passage of time as a result of such factors as muscle atrophy, change in weight, or progress in rehabilitation practices [109, 110]. This tends to reduce the effect of the static design including the ones that have been optimized in the long term without doing regular adjustments and updates which may not be possible in some cases and may not be cost effective. The changes may also cause discomfort and misalignment and will need to be recalibrated often or replaced with an entirely different prosthetic design. These constant updates may take too much time and be expensive to the user both in the short and long term [111].

5.3.3 Integration of EMG signals for prosthetic control

Integrating neural and muscular signals with prosthetic legs results in a smoother and more natural movement. This approach allows movement that is closer to natural movement than conventional designs, providing finer control and improving overall functionality for the user. EMG sensors are increasingly utilized as they capture muscle activities in the residual limb and subsequently help in prosthetic control signal generation. Despite advancements in this field, technology's effectiveness hinges on the user's muscle fitness, level of fatigue, and sensor signal capture. This variability poses challenges in consistent control for some device users, especially as signal quality can fluctuate over time due to user condition or environmental factors [112, 113].

6. Future directions

An interdisciplinary approach, integrating artificial intelligence (AI), biomechanics, and digital health systems, is revolutionizing the future design of prosthetic

limbs. These innovations not only aim to restore basic functions but also focus on improving user performance, comfort, and overall quality of life. Real-time performance and user-intuitive capacity of making adjustments according to the user will become more feasible as prosthetic development continues to grow. This section describes the future of further prosthesis development, with a focus on AI-powered individualization, predictive responsiveness, full-body health integration, as a way to increase relative user freedom and mobility.

6.1 AI for personalization and adjustments

The most dramatic change of the modern limb software ecosystem is probably with AI, which holds the potential to respond in adaptive and user-specific ways to the surroundings. Although the previous generations of prosthetics were fixed, AI-powered prosthetics systems work on the analysis of the user behavioral patterns, the need anticipation, and on-the-fly changes. These serve to minimize any compensation by the user and aid in a more natural and efficient walking pattern. Adaptive prosthesis limbs can dynamically vary their behavior with changes in walking speed, terrain, and physiology, such as fatigue to achieve the most naturalistic behavior of any artificial limb [89, 114].

6.1.1 Machine learning for customized fit

One of the main goals of prosthetics is to provide consistently comfortable and biomechanically optimal fitting. A promising solution lies in the application of machine learning, which enables prosthetic systems to learn from individual data on gait kinematics, pressure distribution, and changes in limb volume. Continuous analysis of this information allows the system to make subtle, automatic adjustments to socket fit and alignment throughout the day, thereby improving support and reducing the development of skin irritations and pressure sores. As a result, body-prosthesis integration is enhanced, promoting smoother movement patterns and sustained user comfort during long-term use [87, 115].

6.1.2 Predictive analytics for real-time adjustments

One of the major drawbacks of conventional prosthetics is the inability to anticipate changes in movement or terrain. The integration of predictive analytics into intelligent prosthetic systems addresses this limitation by enabling real-time predictions. These devices contain embedded sensors that capture data on gait patterns, ground reaction forces, and muscular activity, which are then processed by machine learning models to anticipate user intent before it occurs. This capability ensures smoother transitions across different surfaces, including slopes, stairs, and uneven ground, while reducing cognitive effort and lowering the risk of falls. Beyond enhancing safety, such intelligent systems also improve user confidence and promote greater independence [89, 116].

6.1.3 Integration with other health data

Along with enhancing mobility, the future of prosthetics lies in the integration of overall health. AI-driven prosthetic systems are increasingly designed to connect wirelessly with wearable health monitors, smart devices, and electronic medical

records. This integration enables continuous, real-time tracking of key physiological parameters such as heart rate, muscle fatigue, hydration level, and joint stress [117]. The system can also automatically adjust mechanical settings when thresholds indicate excessive strain that could risk user injury. Furthermore, clinicians can remotely access this data to monitor user progress, modify therapy regimens, or schedule maintenance interventions. These developments illustrate that prosthetic limbs are evolving beyond mobility devices to function as comprehensive personal health systems [118].

6.2 Advanced lightweight, durable materials

Recent progress in materials science, especially in the design of lightweight, strong, and durable materials, is shaping the future of prosthetic limb technology. Among these materials, carbon fiber remains the most widely used because of its high strength-to-weight ratio. This makes it particularly suitable for everyday use in high-performance products. For example, it allows users to walk, run, and carry out dynamic activities while using less energy, helping prostheses feel closer to the natural biomechanics of the human limb [119].

With the introduction of tougher fibers and newer composite materials, prostheses have shown better strength and improved shock absorption, which also helps to reduce fatigue. These improvements not only enhance performance but also lessen pain and injury in the residual limb. This is especially important in cases of high-impact activity, such as those experienced by athletes or highly active individuals. Recent studies have been conducted on carbon fiber composite, biodegradable polymer, and nanomaterial to design the next generation of prosthetic limbs that can be both functional and eco-friendly [120, 121].

6.2.1 Carbon fiber and composite innovations

Carbon fiber (CF) has become one of the most important materials in prosthetic fabrication because it provides high mechanical strength while still being lightweight. This combination makes it possible to return energy with each step, helping users walk or run with less fatigue and greater responsiveness. The strength of CF also allows prosthetic limbs to cope with demanding activities, such as running or jumping, without reducing performance or compromising user safety [122].

In addition, progress in composite engineering—particularly the use of layered carbon fiber combined with resins or thermoplastics—has improved the flexibility and shock-absorbing capacity of prosthetic limbs. These improvements make prosthetic devices more durable and adaptable, particularly under physically demanding conditions. The updated structures reduce the load placed on the residual limb, which helps to lower discomfort and minimizes the long-term risk of overuse injuries. Athletes and physically active individuals, in particular, can benefit from such technology, as they require equipment capable of delivering high strength, speed, and momentum across diverse terrains and environments [123, 124].

6.2.2 Biodegradable and eco-friendly materials

The growing importance of sustainability in the production of medical devices has prompted scientists to consider new materials that are biodegradable or less harmful to the environment that could be used in artificial limbs. Conventional materials such

as thermoplastics and metals pose environmental concerns, as they take a long time to decompose. In contrast, bio-composites, plant-based fibers, and natural resins provide a more sustainable substitute [125].

The adoption of biodegradable prosthetics not only offers ecological benefits but can also serve as a cost-effective solution in low-resource settings. Using locally sourced, renewable materials can lower production costs and improve access to prosthetic care in underprivileged regions. These innovations support the development of a circular production model, encouraging the use of recyclable components while maintaining acceptable standards of strength, durability, and function [61, 126].

6.2.3 Nanomaterials for enhanced strength-to-weight ratio

Nanotechnology introduces a revolutionary frontier in prosthetic material science. By integrating nano-reinforced polymers, carbon nanotubes, and metal-based nanocomposites, manufacturers can produce prosthetic components with dramatically improved mechanical properties. These materials provide exceptional tensile strength, fatigue resistance, and impact absorption while keeping the device ultra-lightweight [127].

Compared to polyurethane, which is often used in prosthetic feet, carbon nanotube (CNT) natural rubber composites with just 1 wt% CNTs show a 25% increase in tensile strength. Not only that, but these composites also offer 20% better dimensional stability and 15% greater heat resistance than regular natural rubber. This means CNT-enhanced prosthetics are not only stronger but also more durable, making them a great option for people who need reliable, long-lasting performance in their daily activities [128]. These characteristics are particularly important for users with high activity levels, as they ensure both comfort and consistent performance in real-life conditions. As research advances, nanomaterials-based prosthetic limbs are expected to set new benchmarks in terms of ergonomic functionality and mechanical reliability for a wide range of amputee populations globally [129, 130].

6.3 Affordable, accessible prosthetic innovations

While cutting-edge technology continues to advance the functional sophistication of prosthetic limbs, the challenge of affordability remains unresolved for a large portion of the global amputee population. High-quality prosthetics often come with prohibitive costs, making them inaccessible to people in low-income or underserved regions. Therefore, future innovation must prioritize both technological progress and economic feasibility to ensure equitable access [131].

The current efforts of researchers and developers include lowering manufacturing prices through affordable 3D printing, biodegradable materials, and open-source design. Additionally, nonprofit organizations, humanitarian missions, and subsidized healthcare programs are contributing significantly increase prosthetic access in developing regions. These initiatives support a future vision where functional and advanced prosthetics are not just technological successes but are available to amputees who need them to regain autonomy and mobility in their daily lives [100, 132].

6.3.1 3D printing for mass production

3D printing has come up as a radical way of mass production of prosthetic limbs. In comparison with traditional ways of manufacturing, 3D printing cuts drastically

the time as well as grants the opportunity to customize immensely. At present, it is possible to fabricate a complete prosthetic limb within a few hours, using minimal material waste, which makes this approach particularly suitable for application in resource-limited environments [102].

The most significant advantage of this technique lies in its capacity for personalization. For instance, three-dimensional scans of a patient's residual limb can be translated into a socket design that ensures a precise anatomical fit, provides comfort, and maintains biomechanical compatibility. This is especially valuable in regions where the availability of trained prosthetists is limited. Furthermore, additive manufacturing allows local production of prosthetic components, thereby reducing dependence on centralized supply chains that may be disrupted during natural disasters or in rural settings. Collectively, these attributes position 3D printing as a transformative tool for restoring mobility and enhancing independence in millions of individuals living with limb loss worldwide, particularly within developing regions where large-scale, integrated fabrication facilities are not feasible [133, 134].

6.3.2 Global initiatives for equitable access

Nevertheless, millions of individuals around the world cannot access basic prosthetic treatment because of inaccessibility, cost, and logistic-based challenges, as well as educational hurdles. National governments, non-governmental organizations, and international agencies have undertaken significant efforts to address the gap in access to prosthetic care. These initiatives include the donation of prosthetic devices, the establishment of local manufacturing centers, and the introduction of training programs to prepare community members as prosthetic technicians [135, 136].

Such programs are designed to promote long-term sustainability by enabling local healthcare facilities to provide continuous support for amputees. Training local professionals in the fitting, adjustment, and maintenance of prosthetic limbs is particularly important, as it ensures continued care beyond the initial fitting. Such programs not only offer technical support but also support social reintegration and restoring mobility, which enables the individuals who receive such programs to play a more active part in society and enhance their economic prospects. Through proper funding and international cooperation, such international projects should open the road to the universal availability of prosthetics [137].

7. Conclusions

Functional mobility is severely affected by gait abnormalities due to amputation, musculoskeletal injuries, or neurological disorders, causing discomfort, and fatigue among individuals, as well as the risk of joint degeneration and muscle strain. The biomechanical problems such as lack of proper weight distribution, abnormal joint angles, and inefficient propulsion, among others, affect the natural cadence and stability of human walking. Although prosthetic mobility aids have significant importance in mobility, the conventional models lack the capacity to emulate the complexity of natural motion since they are rigid in construction, lack flexibility, and are cumbersome when used over prolonged periods.

The recent developments in the world of prosthetics provide some promising solutions. Adaptive artificial intelligence, dynamic alignment systems, and energy-storing materials combine to improve gait performance, creating prosthetic limbs that move

in real time relative to the movements of the user and the environment. These types of innovations make prosthetic devices more comfortable, stable, and effective, bringing them closer to replicating the natural biomechanics of human joints. Continuous monitoring of movement and real-time responses to sensor data contribute to the development of adaptive, personalized prosthetic systems that minimize physical strain and provide greater control for the user.

Nevertheless, significant challenges remain. Replicating the coordinated function of the muscular, skeletal, and nervous systems is an exceptionally complex task. Future research should focus on enhancing the sensitivity of prostheses to different surfaces and activities, while also improving their strength and adaptability to environmental conditions. Long-term usability can be supported through advances in breathable materials, ergonomic socket design, and strategies for effective weight and pressure distribution. In parallel, intuitive control systems that rely on sensory feedback are essential for achieving seamless integration with the user and for fostering psychological acceptance of the artificial limb.

The issue of accessibility will persist, as many low-income individuals in underserved communities remain unable to afford advanced prosthetic devices. Research into cost-effective technologies—such as modular designs, open-source development, and 3D-printed components—offers promising solutions to bridge this gap and promote equitable mobility on a global scale.

The prosthetic mobility sector is on the verge of major advances. The integration of robotics, artificial intelligence, biomechanics, and materials science is expected to yield prosthetic systems that respond more naturally, adapt to a broader range of tasks, and are easier to control. Future devices should not only restore lost movement but also expand human mobility, enabling navigation of complex environments, participation in athletic activities, and overall improvements in quality of life.

Modern prosthetic limbs are no longer viewed merely as medical replacements but as genuine extensions of the human body. These smart systems are designed to adapt individually, sense and interact with their surroundings, and integrate with other technologies, empowering users to regain independence and extend the boundaries of human mobility.

Acronyms and abbreviations

AI	artificial intelligence
BCI	brain-computer interface
CF	carbon fiber
EMG	electromyography
FSR	force sensing resistor
GRF	ground reaction force
ML	machine learning
TFA	transfemoral amputation
TTA	transtibial amputation

Author details

Md Enamul Hoque, Md Sakif Zawad* and Nur Md Atiquzzaman Rasel
Department of Biomedical Engineering, Military Institute of Science and Technology,
Dhaka, Bangladesh

*Address all correspondence to: dipro920@gmail.com

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Treating Burn Sequelae: A Surgical Guide

Luiz Philipe Molina Vana and Jun Wu

Abstract

The management of severe burns constitutes a formidable challenge in modern medicine. The inherent complexity and severity of extensive burns render their treatment a demanding task that evolves in tandem with advancements in medicine. Historically performed by general surgeons, burn care has transitioned into a multidisciplinary endeavour, integrating expertise from numerous medical and non-medical fields. Consequently, the effective treatment of major burn injuries depends on a large, collaborative team. However, a direct consequence of improved survival rates has been the increased incidence of sequelae. The management of these functional and esthetic complications continues to pose significant hurdles, even within centres of excellence. Optimal planning and execution of treatment during the acute phase are critical for mitigating sequelae. Clinical observation reveals a rising incidence of burn sequelae, a trend attributed to the improved survival rates of patients following acute injury in the recent decades. It is crucial to recognize that the pathophysiology of most burn sequelae, whether functional or esthetic, is rooted in the development of hypertrophic scarring. Therefore, the quality of care delivered during the acute phase represents the most significant prognostic factor for the subsequent development of these complications. While many conventional therapeutic strategies established decades ago remain fundamental to burn care, the paradigm for managing sequelae has shifted. Non-surgical alternatives have gained prominence, leading to new approaches for managing the scars that are the primary drivers of sequelae. Modalities such as CO₂ laser, pulsed-dye laser, intense pulsed light, and microneedling are now integral components of treatment in specialized centres.

Keywords: burn, burn reconstruction, burn sequelae, contractures, hypertrophic scar, scar management, post-burn complications

1. Introduction

The management of severe thermal injury constitutes one of the most formidable challenges in contemporary medicine. The paradigm of care has evolved from an isolated surgical practice into a comprehensive, multidisciplinary endeavour, incorporating advances in intensive care, wound healing pathophysiology, and tissue engineering [1]. This evolution has led to the unprecedented survival rates, particularly in paediatric populations, where patients with burns covering up to 98% of their total body surface area can now survive [2]. A direct consequence of improved survival, however, is the increased incidence and prevalence of long-term burn sequelae.

The management of these complications remains a significant clinical challenge, even in specialized centres of excellence [3, 4].

The pathophysiology of most burn sequelae, both functional and esthetic, is fundamentally linked to aberrant scar formation, namely hypertrophic and keloid scarring [4]. Therefore, the quality and timeliness of treatment during the acute phase are the most critical prognostic factors [5–7]. The duration of wound healing is a key indicator; wounds requiring more than 10 days to epithelialize have a 33% probability of developing hypertrophic scars, a risk that increases to 80% after 21 days [1]. While conventional therapies remain foundational, the therapeutic landscape has expanded to include advanced technologies such as tissue engineering and energy-based devices like CO₂ and pulsed-dye lasers [8].

Given this complexity, the standardization of care through the established protocols is essential, particularly in academic and training institutions. The development and implementation of treatment algorithms serve to facilitate this process, ensuring uniformity and quality of care. The continuum of burn management is conventionally divided into two distinct phases: the acute phase, which spans from the initial injury until complete wound closure, and the late or reconstructive phase, which begins thereafter. This text focuses on an algorithm for the late phase, emphasizing the prevention and treatment of burn sequelae.

Burn sequelae, with the exception of unavoidable outcomes like amputations from high-voltage electrical injury, are intrinsically related to the healing process. Deficient healing, influenced by acute care and patient-specific factors, leads to scars of poor quality characterized by loss of elasticity, altered texture and thickness, dyschromia, and contracture.

For clinical and therapeutic purposes, sequelae are broadly classified as either functional or non-functional. Functional sequelae are defined by the impairment of normal physiological function. Severity is context-dependent and ranges from mild (e.g. slight limitation in limb extension) to severe (e.g. complete inability to extend a limb, resulting in a fixed contracture). A universal severity classification is lacking; thus, a thorough assessment of each unique clinical situation is required to determine the appropriate treatment strategy.

Non-functional sequelae, also termed esthetic sequelae, involve alterations in appearance without direct functional impairment. Examples include alopecia, loss of eyebrows, and changes in skin colour and texture. Although significant to patient quality of life, the correction of these issues is generally not prioritized over functional restoration. The therapeutic hierarchy dictates that functional sequelae be addressed before non-functional ones. In practice, however, functional and esthetic goals are often addressed concurrently, aiming for the best possible cosmetic result during a functional reconstruction [9].

The timing of surgical intervention is dictated by clinical urgency. Emergencies, such as severe ectropion with risk of corneal injury or microstomia impairing nutrition, necessitate early surgery. In non-urgent cases, procedures are typically deferred for at least six months post-injury to allow for scar maturation and subsidence of the inflammatory response, which minimizes the operative challenges like bleeding [9].



The treatment cascade for functional sequelae begins with optimizing non-surgical modalities, such as compression therapy, massage, silicone application, physical therapy, and advanced treatments like laser therapy and microneedling, ideally combined

with drug delivery. Surgical intervention is considered once the potential benefits of these conservative measures have been exhausted. Throughout this process, the treatment plan remains dynamic, allowing for a return to non-surgical strategies as needed to support and enhance surgical outcomes.

2. Non-surgical treatment

Non-surgical treatment is an integral component in the management of all types of burn sequelae and should be consistently evaluated throughout patient follow-up. At any stage of care, these modalities must be considered, and in some clinical scenarios, they may constitute the sole intervention necessary. Recent technological advancements have led to the significant improvements in clinical outcomes. The therapeutic armamentarium includes compression therapy, massage, silicone application, physical therapy, laser treatment, and microneedling. The latter two techniques are ideally combined with drug delivery to enhance efficacy, as illustrated in **Figure 1**.

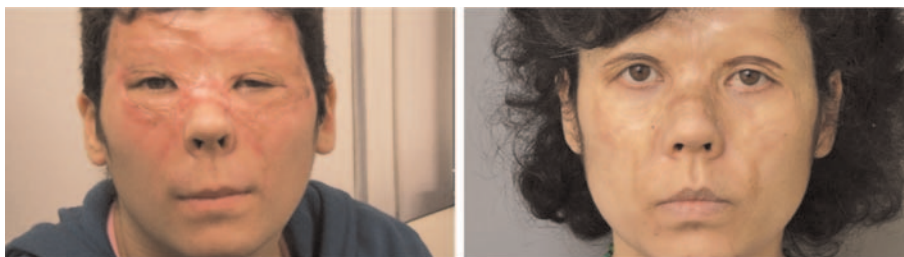


Figure 1.
Example of a non-surgical treatment with compression garment, laser, and small Z-plasty in the lateral and medial eye regions.

3. General principles

Some principles must be respected in all patients:

- Preservation of expressions;
- Normal appearance at conversational distance;
- Balanced and symmetrical face;
- Imperceptible scars;
- Skin texture that allows for at least corrective makeup;
- Preservation of movement dynamics.

3.1 Definitions in burn sequelae

The indication for treatment is determined by the specific type of sequela, which primarily includes contractures, retractions, adhesions (synechiae), and pathological scars [10, 11].

3.1.1 Linear band or linear contracture

These retractions manifest as palpable, linear, cord-like bands, as shown in **Figure 2**. Typically, these retractions do not present as solitary bands but are found in complex patterns or multiple formations.



Figure 2.
Example of linear band in the axilla and neck.

3.1.2 Broad contractions or retractions

A contracture is defined by a reduction in the range of motion, typically affecting a joint. Unlike a linear retraction, this limitation is caused by a diffuse area of inelastic scar tissue rather than a discrete, restrictive cord-like band as illustrated in **Figure 3**.



Figure 3.
Example of broad contracture in the neck.

3.1.3 Synechiae

A synechia is a particularly severe form of contracture, characterized by the pathological fusion of adjacent anatomical surfaces that are normally separate (**Figure 4**).



Figure 4.
Example of synechiae in the neck.

3.1.4 Pathological scars

These diagnostic categories are often conflated; however, a clear differentiation is essential for effective therapeutic planning, as management strategies vary substantially depending on the underlying pathology.

3.1.4.1 Hypertrophic scars

Hypertrophic scars are the most prevalent type of post-burn scar, typically arising from deep partial-thickness burns that have healed spontaneously (**Figure 5**). These scars begin to form shortly after the injury and are clinically characterized by being



Figure 5.
Example of hypertrophic scar.

raised, erythematous, indurated, and often pruritic, while remaining confined within the boundaries of the original wound. They generally show a favourable response to non-surgical management, especially when therapy is initiated early in the scar maturation process [10, 12].

3.1.4.2 Keloids

Keloids are pathological scars that present as firm, rubbery lesions, or shiny, fibrous nodules. Their coloration can range from pink or skin-toned to red or dark brown. A defining characteristic of keloids is their tendency to grow beyond the boundaries of the original wound (**Figure 6**). In contrast to hypertrophic scars, keloids exhibit an unpredictable and often poor response to non-surgical treatments [10].



Figure 6.
Keloids developed as a result of acne vulgaris.

3.2 Commonly performed procedures and surgeries

- **Excision and primary closure:** Simple excision with primary closure is the most fundamental technique for managing certain scar lesions. The procedure involves the complete removal of the lesion followed by direct, edge-to-edge suturing of the wound. In instances where the size or location of the lesion precludes complete removal in a single procedure, staged or serial excisions are performed [1, 12].
- **Local flap:** Local flaps are the preferred surgical method for the release of linear scar bands and minor contractures. The most commonly utilized technique is the Z-plasty, typically designed with 60-degree angles, along with its variations such as sequential Z-plasty (Z-sequence) and the double-opposing Z-flap. This technique can be safely performed within scarred tissue, provided that meticulous care is taken to preserve the vascularity of the flaps by ensuring they are sufficiently thick and minimizing subcutaneous dissection [1, 13].
- **Skin grafts:** The surgical management of burn sequelae preferentially utilizes unmeshed sheet grafts, either split- or full-thickness. This preference is based on the superior clinical outcomes associated with sheet grafting compared to meshed techniques, including an improved esthetic appearance (colour and texture), a reduced rate of pathologic scar formation, and the containment of incisional

scarring to the suture lines. The principle of replacing “like with like” governs donor site selection: scalp grafts are ideal for facial resurfacing due to their excellent tissue match, whereas plantar arch skin is favoured for reconstructing palmar defects [13–18].

- **Tissue expander:** Tissue expansion is a procedure that can reduce scarring and yield high patient satisfaction, but it requires significant patient cooperation and adherence. Despite its conceptual simplicity, the selection and placement of expanders involve a notable learning curve and a risk of complications, such as suture dehiscence and distortion of adjacent structures. Outcomes tend to be less favourable when the expanded flap must be elevated and transposed. In particular, the use of expanders on the face and neck can lead to challenging results, including loss of natural contours and traction on nearby features, which may result in an esthetically suboptimal appearance.
- **Dermal regeneration matrix:** Dermal regeneration templates are generally not considered a first-line reconstructive option, given their substantial cost and the demanding learning curve required for consistent results. Their primary advantage lies in the mitigation of donor site morbidity by allowing the use of thinner split-thickness skin grafts. However, this is balanced by a unique profile of potential complications, including infection, matrix loss, failure of the definitive graft to revascularize, and late-stage contraction. The adjunctive use of Negative Pressure Wound Therapy (NPWT) has been demonstrated to mitigate these risks, improving the rates of matrix incorporation and graft take while reducing hospital stays and enhancing patient comfort [13, 19].
- **Regional and expanded flaps:** Regional flaps are the optimal solution for specific reconstructive challenges, like breast reconstruction, but their use can be limited by the insufficient local tissue volume or surface area. These limitations can be overcome by utilizing tissue expansion to augment the available donor tissue before flap transposition. While this staged approach is demanding, it produces reliable and esthetically favourable outcomes. The success of this technique is contingent upon technical proficiency with both the principles of tissue expansion and the design and execution of the regional flap itself [1, 20].
- **Free flaps:** Microsurgical flaps are utilized in complex cases characterized by severe functional impairment, particularly when no other reconstructive options are viable. The most commonly employed flaps for these indications include the anterolateral thigh (ALT) flap, the transverse rectus abdominis myocutaneous (TRAM) flap, and the latissimus dorsi flap [21].
- **Hair implant:** For the reconstruction of the eyebrow, hair transplantation serves as the first-line surgical modality. This procedure can produce superior esthetic outcomes that closely resemble a natural brow; however, achieving optimal density often necessitates multiple sessions, typically two to three. A critical aspect of patient counselling involves explaining the requirement for lifelong maintenance, specifically the regular trimming of the transplanted grafts. This is because the follicles retain the anagen-phase dominance of their scalp donor site, resulting in continuous growth unlike that of native eyebrow hairs [1, 13].
- **Corticosteroid infiltration:** Intralesional corticosteroid therapy is most commonly performed with triamcinolone acetonide at a concentration of 20 mg/ml.

The technique requires precise intradermal administration directly into the fibrotic scar tissue; care must be exercised to avoid injection into the underlying subcutaneous plane, which can lead to fat atrophy. The treatment regimen typically involves a series of injections at monthly intervals, with most patients requiring approximately three sessions to achieve a significant therapeutic response.

3.3 Reconstruction ladder

For decades, the “reconstructive ladder” has served as a guiding principle in plastic surgery, dictating a stepwise progression from simple to complex solutions for defect closure. The fundamental tenet of this framework is to select the least complex method that will achieve a successful outcome. However, contemporary reconstructive philosophy has evolved this concept into the “reconstructive elevator,” which acknowledges that for specific, complex defects, the most effective and efficient solution may be an advanced technique, thus justifying the bypassing of simpler options from the outset (Figure 7) [22].

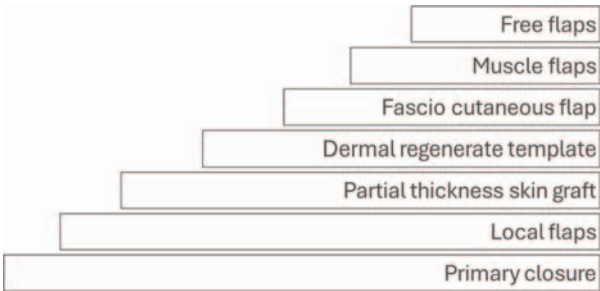


Figure 7.
The reconstruction ladder.

4. Algorithm for treating functional sequelae

The decision to proceed with surgical management is made upon the failure or exhaustion of non-surgical modalities. Subsequently, the formulation of a surgical plan is contingent upon a definitive diagnosis of the specific pathology being addressed, which guides the selection of the optimal procedure (Figure 8).

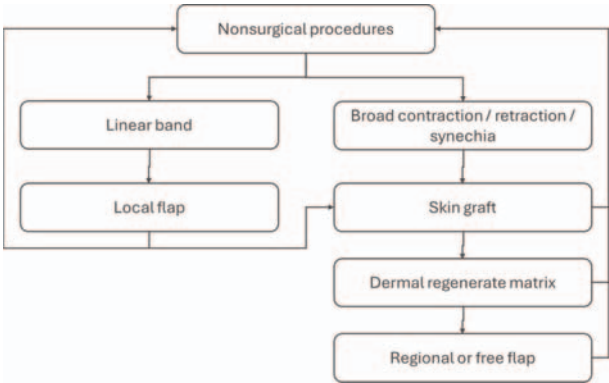


Figure 8.
Overview of functional sequela treatment.

4.1 Linear band

The formulation of a surgical plan is contingent upon an accurate diagnosis of the sequela. In the presence of a linear scar band causing contracture, local tissue rearrangement *via* Z-plasty is the indicated procedure. Common variations, including sequential and double-opposing Z-plasties, may be employed for longer or more complex bands. The principal advantage of this technique is its ability to elongate a contracted axis by reorienting local tissue through the transposition of triangular flaps. The theoretical gain in length is directly proportional to the angle of the flaps utilized, as outlined in **Table 1** [23].

The fundamental principle of Z-plasty is the transposition of two interdigitating, triangular flaps to lengthen a linear scar contracture (**Figure 9**). While technically uncomplicated, successful execution is contingent upon several critical details. To prevent retraction and ischemia at the flap tip, the limbs of the “Z” should be incised with a slight curvature. The limbs must also be of equal length to ensure symmetric transposition and tension-free closure. Most importantly, dissection in the subcutaneous plane should be performed judiciously, incising only the amount necessary to permit flap transposition. This approach ensures the preservation of the subdermal vascular plexus, a paramount consideration when operating on scarred or previously burned tissue with compromised vascularity (**Figures 9** and **10**). The standard surgical technique is illustrated in the accompanying video (**Video 1** <http://bit.ly/4n8IkA4>) [23–25].

Of particular note, the release of the underlying longitudinal tension is achieved upon incision alone, permitting the spontaneous transposition of the flaps into their recipient sites with minimal to no subcutaneous undermining. This illustrates the efficiency of the technique in redistributing tissue forces to achieve contracture release.

Angles of z-plasty	Theoretical gain in length (%)
30–30	25
45–45	50
60–60	75
75–75	100
90–90	125

Table 1.
Z-Plasty, angles, and theoretical gain.



Figure 9.
Clinical example illustrating the use of Z-plasty in the axillary region and neck.

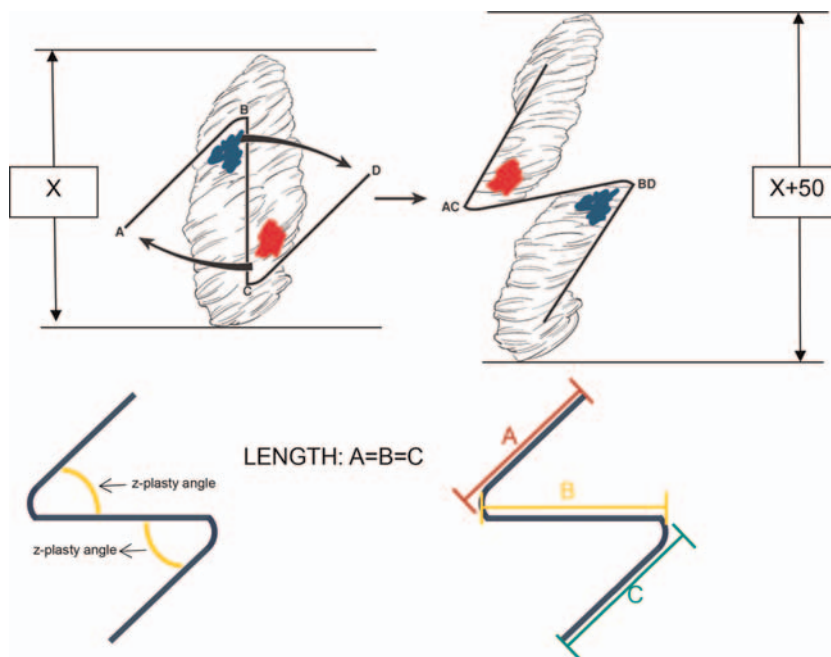


Figure 10.

Schematic representation depicting the preoperative marking for the Z-plasty technique.

4.2 Retraction

The indicated surgical approach for a retraction or synechia is a complete release of the restrictive tissue. This is typically achieved *via* an incision that transects the scar without excising underlying tissue, unless the tissue quality is exceptionally poor. The inherent tension within the scar results in immediate separation of the wound edges upon incision, creating a resultant soft tissue defect that requires subsequent coverage. The primary and most common method for covering such defects is the application of a skin graft. Should skin grafting not be a viable option, a dermal regeneration matrix is considered the second-line treatment. The third-line and most complex option involves the use of regional or distant (microsurgical) flaps.

4.2.1 Skin graft

The standard of care for the surgical reconstruction of burn sequelae involves the use of unmeshed sheet grafts [26]. This preference is based on their demonstrated superiority over meshed grafts in yielding favourable esthetic outcomes—including improved texture and colour match—and better functional results. Furthermore, sheet grafting is associated with a lower incidence of pathologic scar formation (hypertrophic and keloid) and confines incisional scarring to the graft's perimeter (**Figure 11**) [13–18, 27].

While partial-thickness grafts are most commonly employed (**Figure 12**), specific clinical scenarios dictate the choice of graft thickness. Thick split-thickness skin grafts are recommended for areas subject to high mechanical stress, such as the hands and joints, assuming donor site availability. Conversely, full-thickness skin grafts are the optimal choice for eyelid reconstruction, as their inherent resistance to secondary contraction mitigates the high rate of ectropion recurrence. Donor site selection is governed by the



Figure 11.
 First case, a cervical contracture release with split-thickness skin graft. Pre-operative, intra-operative, and post-operative views. Note the enhance of the jawline contour. The second case involved severe facial scarring secondary to poor wound healing and loss of a previous skin graft. The entire affected area was resurfaced with a new split-thickness skin graft harvested from the scalp. Note the excellent colour match and the significant improvement in skin texture.

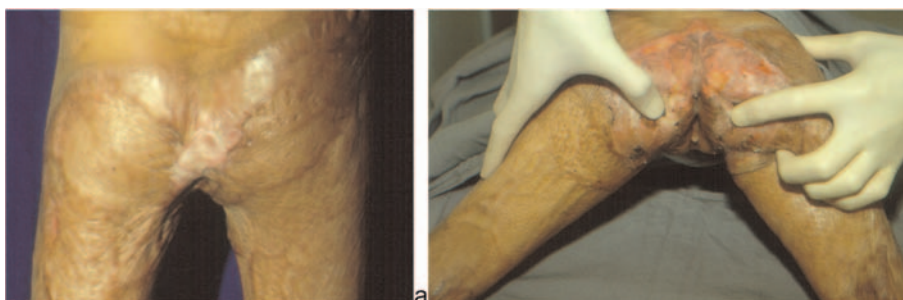


Figure 12.
 Surgical release of a gluteal synechia and subsequent skin grafting, performed to restore the intergluteal cleft and facilitate proper hygiene.

principle of replacing “like with like”; consequently, the scalp is a preferred donor site for facial resurfacing, and the plantar arch is favoured for palmar defects [13–18, 27].

In scenarios where coverage with a standard split-thickness skin graft is not feasible, alternative reconstructive options are considered. The primary contraindications for standard grafting include a paucity of suitable donor sites or a history of previous graft failure. In such cases, the second-line option is the application of a dermal regeneration matrix. This approach is indicated provided that a very thin split-thickness skin graft can still be harvested to cover the matrix [23]. In the event that no suitable donor tissue is available for any form of grafting, the defect must be addressed with vascularized tissue, such as a regional or microsurgical free flap [20].

4.2.2 Dermal substitutes

For the last three decades, dermal substitutes have been instrumental in advancing the care of both acute burns and their resulting sequelae. Originally established for acute wound management, the indications for these dermal regeneration templates have expanded to include various reconstructive challenges where achieving high-quality, pliable skin coverage is paramount to the final outcome (**Figure 13**) [28, 29].

Dermal substitutes have been instrumental in advancing the treatment of both acute and chronic burns, as well as their associated sequelae, over the last three decades. These bioengineered materials are broadly categorized by their structure and composition. They may consist of a single layer, which can be covered with a skin graft either immediately or in a delayed fashion, or a double layer. Bilayer constructs typically feature a collagen-based scaffold covered by a protective film (e.g., silicone), which must be vascularized by the host bed before the definitive skin graft is applied. The origin of these matrices varies, including allogeneic sources and synthetic compounds, with some products being pre-seeded with cells such as fibroblasts or keratinocytes. Numerous commercial products are available, including Integra®, Matriderm®, Pelnac®, Hyalomatrix®, and Nevelia®, each with unique characteristics but similar underlying principles [21].

Integra®, introduced in the 1990s, was the first commercially available artificial dermis. It is a bilayer template composed of a bovine collagen and glycosaminoglycan matrix, covered by a thin silicone layer that prevents desiccation. Its application is a two-stage procedure. The first stage requires the complete adherence of the matrix to the wound bed to facilitate angiogenesis and remodelling, which results in the formation of a so called “neodermis.” The second stage, which involves removing the silicone layer and applying a split-thickness skin graft, is performed once the scaffold is adequately vascularized—typically within three weeks, or as early as 14 days when used in conjunction with Negative Pressure Wound Therapy (NPWT) (**Figure 14**) [30].

Matriderm® is a single-layer matrix composed of bovine collagen and elastin, available in 1-mm and 2-mm thicknesses. It is a flexible sheet that conforms well to wound topography and provides a mild haemostatic effect. The 1-mm version can be used in a single-stage procedure with immediate application of the definitive skin graft, whereas the 2-mm version requires a delayed grafting procedure [30].

The use of a thin split-thickness skin graft is preferred with these matrices, and clinical results demonstrate the significant benefits in terms of elasticity and ease of



Figure 13. Surgical management of a chronic ulcer that developed within an unstable skin graft on the wrist. The treatment consisted of complete excision of the ulcer and surrounding scar tissue, followed by reconstruction with a dermal regeneration matrix and a subsequent thin split-thickness skin graft.



Figure 14.
Reconstruction of a neck contracture with a dermal regeneration template. Pre-operative, intra-operative and post-operative sequence.

application. The adjunctive use of NPWT has been shown to enhance the matrix integration, accelerate vascularization and improve conformity on contoured surfaces, thereby reducing the complications [31, 32].

The choice of a specific dermal matrix depends on product availability and the clinical indication. Bilayer matrices, which typically have a silicone outer layer, require a longer period for vascularization and are more challenging to apply to complex, curved surfaces. Based on these characteristics, single-layer matrices are often preferred for areas requiring early rehabilitation, such as the hands, or for anatomically complex regions. The use of bilayer matrices is indicated for less-demanding planar surfaces and for providing coverage over exposed tendon or bone [25, 33]. Their two-stage application is advantageous when definitive skin grafting must be delayed due to donor site unavailability. Furthermore, they appear to offer superior dimensional stability, with clinical evidence suggesting less secondary contraction compared to the single-layer templates [31, 32].

4.3 Regional and free flaps

As regional and free flaps are covered in a separate chapter, they will only be mentioned briefly in this section. In the realm of plastic and reconstructive surgery, flaps are a cornerstone for repairing complex defects that arise from trauma, cancer resection, or, notably, severe burns. Unlike a skin graft, which is a thin layer of skin that relies on the underlying wound bed for survival, a flap is a unit of tissue transferred from a donor site to a recipient site with its own blood supply intact. This vascular autonomy makes flaps robust and essential for reconstructing deep, poorly vascularized wounds, covering the exposed vital structures such as bone and tendons, and restoring both function and esthetic contour [34–37].

There are two primary categories of flaps used in this context: regional flaps and free flaps. Both are indispensable in burn reconstruction. Regional flaps offer a simpler, effective solution for specific defects, while free flaps provide the ultimate versatility for repairing complex and extensive burn injuries, enabling surgeons to restore not only the integrity of the skin but also the patient's function and quality of life [35, 36].

4.3.1 Regional flaps

A regional flap, also known as a pedicled flap, is a segment of tissue that is mobilized from an area near the defect and pivoted or tunnelled to cover the wound while remaining attached to its original blood supply through a “pedicle” of tissue.

Characteristics:

- Proximity: The donor site is in the same general region as the wound.
- Intact blood supply: The flap is never fully detached from the body.
- Simpler procedure: These surgeries are generally less complex and time-consuming than free flap procedures as they do not require microvascular anastomosis (the reattachment of blood vessels).
- Limitations: The reach of a regional flap is limited by the length of its pedicle, and the available tissue in the vicinity of a severe burn may also be compromised.

4.3.2 Free flaps

A free flap, or free tissue transfer, represents a more advanced microsurgical technique. In this procedure, a well-defined block of tissue, along with its artery and vein, is completely detached from a distant donor site on the body. This flap is then transferred to the defect, and its blood vessels are meticulously reconnected to recipient vessels at the new site under a microscope.

Characteristics:

- Distant donor site: Tissue can be harvested from virtually anywhere on the body, allowing for optimal tissue matching in terms of size, thickness, and type.
- Microsurgery: Requires specialized training and equipment to perform the delicate vascular anastomosis.
- Versatility: Offers unparalleled freedom in reconstructing complex, large, or specialized defects where local tissue is unavailable or unsuitable.

- Complexity: These are lengthy and demanding operations with a higher risk of complications, such as flap failure due to blood clots in the repaired vessels.

4.3.3 Common flaps in burn reconstruction

The choice of flap for burn reconstruction depends on several factors, including the location and size of the defect, the tissues required (skin, muscle, fascia, or bone), and the availability of uninjured donor sites.

- Anterolateral thigh (ALT) flap:
 - Type: Primarily a free flap.
 - Description: Harvested from the outer thigh, the ALT flap is arguably the most versatile and widely used free flap in modern reconstructive surgery. It provides a large and reliable skin and fat paddle, which can be thinned to match the recipient site. It can also be harvested with a segment of the vastus lateralis muscle if bulk is needed (**Figure 15**).
 - Common uses: Excellent for covering large defects on the extremities, trunk, and head and neck. Its long vascular pedicle provides flexibility in reaching



Figure 15.
Oral sequelae with functional impairment secondary to a chemical burn. Reconstruction was performed using a microsurgical bipartite anterolateral thigh (ALT) muscle flap with a skin paddle. Images show the preoperative condition, the bipartite flap design, and the 1-week postoperative result.

recipient vessels. The donor site can often be closed directly or with a small skin graft, with minimal functional loss.

- Latissimus dorsi flap:

- Type: Can be used as a regional (pedicled) flap or a free flap.
- Description: This large, fan-shaped muscle in the back, with or without its overlying skin, provides a vast amount of well-vascularized tissue.
- Common uses: As a regional flap, it can cover massive defects on the chest wall (**Figure 16**), back, shoulder, and even the head and neck. As a free flap, it is invaluable for large wounds on the lower extremities and scalp where significant soft tissue coverage is required. The functional deficit from losing this muscle is generally well-tolerated.



Figure 16.

Breast reconstruction utilizing an expanded latissimus dorsi myocutaneous flap as a regional flap.

- Radial forearm flap:

- Type: Free flap.
- Description: Sourced from the inner aspect of the forearm, this is a thin, pliable fasciocutaneous (skin and fascia) flap.
- Common uses: Ideal for reconstructing areas that require thin, supple tissue, such as the face, neck (for releasing burn scar contractures), and the dorsum (top) of the hand. Its major drawback is the conspicuous donor site scar on the forearm.

- Groin flap:
 - Type: Regional (pedicled) flap or free flap.
 - Description: One of the earliest described flaps, the groin flap is a reliable option that involves attaching the hand or forearm to the groin for a period of weeks to allow the tissue to transfer.
 - Common uses: Primarily used for covering defects on the hand and wrist. While effective, it requires immobilizing the limb to the body, which can be uncomfortable and has been largely superseded by free flaps in many centres.
- Supraclavicular artery flap:
 - Type: Regional (pedicled) flap.
 - Description: A relatively newer option that has gained significant popularity, this flap is taken from the area above the collarbone.
 - Common uses: It is an excellent choice for releasing severe burn scar contractures in the neck that pull the chin down to the chest (**Figure 17**). The skin provides a good colour and texture match for the head and neck region.

After this phase, the patient is treated as having non-functional sequelae.



Figure 17.
A patient presented with a recurrent contracture in the cervical region, which was managed with surgical release and reconstruction using a regional supraclavicular flap.

5. Algorithm for treating non-functional sequelae

In the context of burn reconstruction, a deliberate terminological distinction should be made. “Non-functional sequelae” is the preferred term over “esthetic sequelae” because the goal of treatment is restorative, not cosmetic. Esthetics, as a philosophical discipline, involves subjective judgments of beauty. The objective of our surgical intervention, however, is to return the patient’s appearance to their pre-burn baseline, a process of restoration rather than enhancement. The initiation of this treatment phase involves a thorough assessment of the patient’s primary concerns and desired outcomes for their scar tissue (**Figure 18**).

The management of non-functional scar sequelae is guided by two primary objectives: improving the intrinsic quality of the scar tissue or reducing its overall surface area. To improve scar quality, non-surgical modalities are the first line of treatment. In this context, energy-based devices and mechanical stimulation, particularly laser therapy and microneedling, have demonstrated significant efficacy in enhancing scar texture, pliability, and overall esthetic appearance.

When the therapeutic goal is scar reduction, surgical excision is indicated. This may be performed as a complete, single-stage procedure or as a series of partial (serial) excisions. Meticulous surgical planning is required to avoid distortion of adjacent anatomical structures, especially on the face, and to ensure a tension-free closure. Excessive tension on the suture line is a primary cause of scar widening and can compromise the final surgical outcome.

Tissue expansion serves as a primary reconstructive option for large scar areas where simple excision is not viable. This technique is distinguished by its unique ability to generate new, well-matched skin, thereby replacing scar tissue with normal tissue. However, its application is not without significant challenges. The literature reports complication rates ranging from 20 to 40%, and the treatment course is demanding for the patient, involving a minimum of two surgeries and numerous interim inflation sessions. In some cases, serial expansion cycles are required to achieve the desired tissue gain. The results can be extremely gratifying for the patient, despite being exhausting (**Figure 19**). We must not underestimate the weight of the flap and, ultimately, the skin. Thus, whenever we need to elevate the flap, results tend

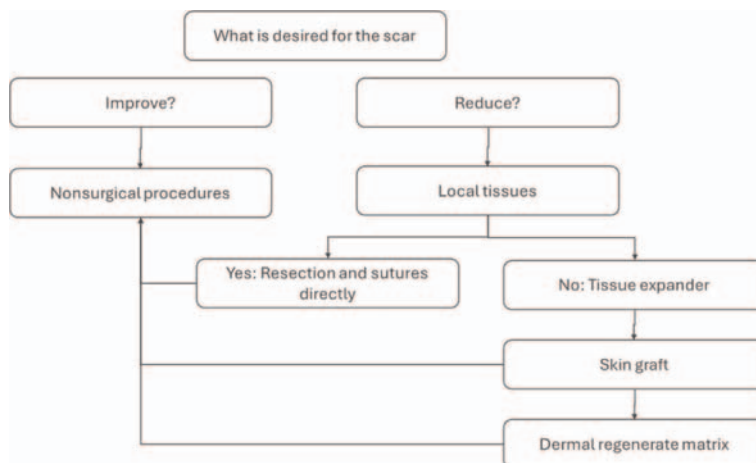


Figure 18.
Overview of non-functional sequela treatment.



Figure 19.
 Example of tissue expansion in the shoulder.

to be poorer. The facial and neck regions often have poor outcomes with significant loss of contours and traction of structures, giving an often-unpleasant appearance [33, 38].

Some points should always be considered (**Figure 20**):

- Incision as far as possible from the expander placement site;
- Incision 2–3 mm away from the scar tissue;
- The placement cavity should be larger than the expander;
- More efficient when placed on a hard surface (bone);
- Closure of the incision in at least three planes;
- You may fill more than indicated on the label (sometimes 1.5–2x);
- Fill 10–15% of the expander during the operation;

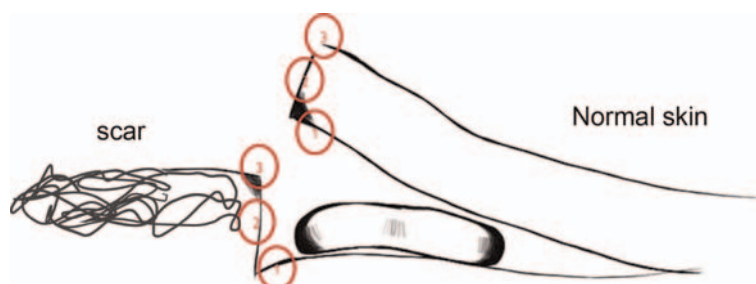


Figure 20.
 A protective suturing method designed to mitigate scar expansion and prevent exposure of an underlying tissue expander, particularly in cases of the compromised skin viability. The suture indicated as (1) represents the key anchoring stitch of this closure. As the first and most important suture, it is placed to secure the expander's position and relieve tension across the wound, thereby preventing the scar from widening. The subsequent sutures, (2) and (3), are then applied to achieve the final apposition of the skin edges and complete the closure. Besides that, the incision is made a few millimetres from the scar.

- Wait 2–3 weeks to start filling the expander;
- Capsulotomy during the flap advance, especially on the basis.

For patients who lack adjacent tissue of sufficient quality for expansion, or for those who are unable or unwilling to adhere to the prolonged treatment protocol, alternative reconstructive strategies must be employed. In these cases, the primary options revert to the use of split-thickness skin grafts or dermal regeneration matrices, as previously described in the management of functional sequelae.

6. Special regions

The application of the preceding treatment algorithms must be adapted for certain anatomical areas that possess unique functional and esthetic requirements. Although the general principles are applicable, specific regions—namely the neck, breast, eyelids, eyebrows, ears, mouth, and nose—necessitate tailored reconstructive strategies.

6.1 Neck

The surgical management of extensive cervical contractures, while guided by the general reconstructive algorithm, incorporates several critical technical modifications. Sustained intraoperative hyperextension is mandatory. The procedure must include a complete release of the platysmal bands *via* a transverse incision, as failure to do so is a known predictor of recurrence. Preoperative assessment and surgical marking should be performed with the patient seated to accurately delineate the extent of the contracture, ensuring the planned incision reaches the unscarred lateral cervical skin. The craniocaudal placement of the incision is dictated by the zone of maximal tension [39]. Postoperative management may involve a compressive orthosis. While incisional release is the standard, pathologic tissue of exceptionally poor quality may necessitate complete excision. Flap-based reconstruction is generally contraindicated due to the unique anatomical challenges of the neck. The thinness of the native skin, the large surface area of defects post-release, and the complex cervical contour make flaps a suboptimal choice, often resulting in significant contour deformities and inadequate functional release [31, 40].

6.2 Breasts

The management of post-burn breast sequelae is stratified by patient age and the nature of the deformity. In prepubescent patients, early intervention with tissue expansion is essential to ensure the skin envelope can accommodate future breast development. In adults, simple linear contractures of the inframammary fold are amenable to Z-plasty. For more complex deformities involving poor skin quality or significant volume loss, particularly of the lower pole, the reconstructive algorithm escalates to include techniques such as excision and grafting, dermal matrix application, or, most definitively, reconstruction with a latissimus dorsi myocutaneous flap [41].

6.3 Eyelids

As the most common sequela affecting the eyelid, the management of post-burn ectropion is contingent upon a precise diagnosis of its underlying cause. A critical

distinction is made between intrinsic ectropion, caused by scarring within the eyelid, and extrinsic ectropion, resulting from traction by adjacent scars. For intrinsic cases, the preferred treatment is a complete incisional release of the contracted tissue and reconstruction with a full-thickness skin graft. To counteract the high propensity for recurrence, a planned overcorrection is an essential component of the procedure. In contrast, the management of extrinsic ectropion requires that the surgical intervention be focused exclusively on the external scar causing the traction; upon its release, the eyelid position typically corrects passively. Only in rare cases involving extensive tissue damage is wide excision and complex reconstruction with grafts or dermal matrices indicated (**Figures 21 and 22**) [42].

6.4 Eyebrow

Numerous techniques have been described for eyebrow reconstruction, including regional flaps and hair-bearing scalp grafts. However, the method that consistently yields the most superior esthetic results is follicular unit transplantation, a technique analogous to that used for treating the androgenetic alopecia. Despite the presence of scar tissue, transplanted follicular units demonstrate a high rate of engraftment, only slightly lower than that observed in non-scarred skin, providing a natural-appearing reconstruction. The primary disadvantage of this technique is the need for lifelong maintenance, as the transplanted hairs retain the continuous growth cycle of their scalp donor site and thus require regular trimming (**Figure 23**) [43, 44].

6.5 Ear

The reconstruction of the external ear represents a formidable surgical challenge. For total auricular defects, the established technique is to create a framework from autologous costal cartilage, which is then draped with the local skin. This approach is often not viable in burn patients due to the compromised quality of the surrounding tissue. In these instances, a more complex solution is required, wherein the cartilage framework is covered with a vascularized temporoparietal fascia flap and then



Figure 21.
Treatment of ectropion with a full-thickness skin graft, noting the change in position of the lower eyelid.



Figure 22.
Example of severe deformation of superior and inferior eyelids corrected with single-layer dermal regenerate matrix. The left nasal ala and oral commissure were reconstructed with local flaps, and the ear was addressed with an external auricular prosthesis.



Figure 23.
Eyebrow reconstruction with hair-by-hair transplant.

surfaced with a skin graft. While effective, this is a technically demanding procedure. In contrast, the management of partial defects, particularly of the common upper pole deformity, can often be accomplished with a simpler technique. The conchal chondrocutaneous transposition flap is a reliable and elegant solution for these cases, providing consistent and esthetically pleasing results with the less surgical complexity (Figure 24) [45, 46].

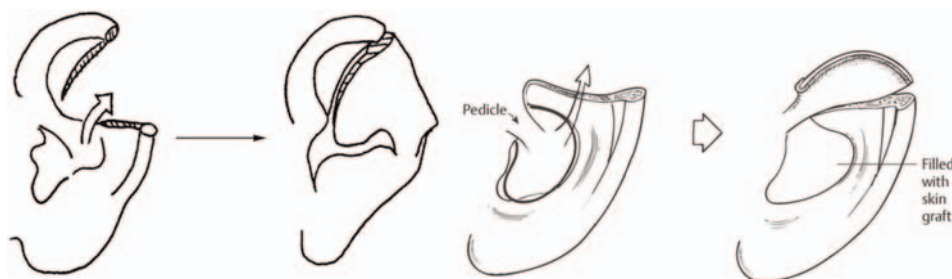


Figure 24.
Illustration of the conchal chondrocutaneous flap correcting defects in two different positions of the upper pole of the ear.

6.6 Mouth

The most common post-burn deformity of the mouth is microstomia, which may be unilateral or bilateral. Its correction is effectively achieved through local tissue rearrangement, typically utilizing Z-plasty or double-opposing Z-plasty. To counteract the significant tendency for recurrence, a planned overcorrection is a critical component of the procedure, aiming to restore the oral commissure to its normal anatomical position in line with the pupil. Another frequent alteration is frequently termed a “ventriloquist’s smile,” a linear scar along the nasolabial fold, which is amenable to release with a sequential Z-plasty. In cases of lower lip ectropion (eclabium), the definitive treatment is contracture release followed by skin grafting (**Figures 25–27**) [47, 48].

6.7 Nose

The nose is an anatomically complex structure, and the most common post-burn sequela is retraction of the nasal ala. For this type of defect, reconstruction with a random pattern nasolabial flap can yield the excellent results. If the skin in the donor area is also scarred or of compromised quality, a surgical delay procedure can be performed on the flap prior to transfer. This technique enhances the flap’s vascularity and mitigates the risk



Figure 25.
Microstomia corrected with local flaps.



Figure 26.
Ventriloquist's smile corrected with Z-Plasty sequence.

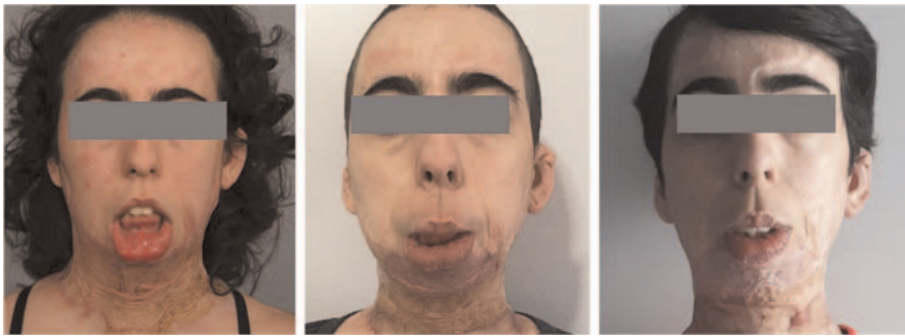


Figure 27.
Lower lip ectropion treated with skin graft.



Figure 28.
Nasal alar reconstruction with random autonomized nasolabial flap.

of necrosis, particularly at the distal tip. For total nasal reconstruction, the paramedian forehead flap is the treatment of choice (**Figure 28**) [49–51].

7. Conclusions

Burn sequelae represent a significant clinical challenge due to their heterogeneity and widespread anatomical impact. Effective management requires not only extensive surgical expertise and versatile techniques but also a long-term, collaborative approach involving both clinician and patient to restore form and function. While surgical reconstruction is a cornerstone of treatment, non-surgical therapies represent a powerful and rapidly evolving frontier. Continued innovation in this area is expected, making it essential for practitioners to remain current with these advancements and to incorporate them as integral options in patient counselling and treatment planning at every phase of reconstruction.

Author details

Luiz Philipe Molina Vana¹ and Jun Wu^{2*}

¹ Hospital das Clinicas HCFMUSP, Faculdade de Medicina, Universidade de Sao Paulo, Divisao de Cirurgia Plastica e Queimaduras, Sao Paulo, Brazil

² Department of Burn and Plastic Surgery, The First Affiliated Hospital, Shenzhen University, China

*Address all correspondence to: drmolina@drmolina.com.br

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