

Research Article

ROBUST Project: Advancing Ubiquitous eHealth Solutions for Fracture Orthopaedic Rehabilitation

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Abstract: The ROBUST (Ubiquitous eHealth Solution for Fracture Orthopaedic Rehabilitation) project represents a pioneering research and innovation initiative. This position paper presents the project's comprehensive approach to revolutionizing bone fracture care through the development of an innovative mobile eHealth platform that integrates advanced RF-based sensing technologies, secure IoT infrastructure, and artificial intelligence-driven rehabilitation protocols. Europe's rapidly ageing population presents unprecedented challenges to healthcare systems, with osteoporosis alone causing over 3.2 million leg and hip fractures annually in those aged 50 and above, with up to 10% becoming non-unions that lead to prolonged immobility, repeated hospital visits, and soaring healthcare costs. ROBUST addresses this critical societal need by developing a smart, connected eHealth solution that enables remote monitoring of patients' healing processes while preserving control, safety, and privacy through reliable and energy-efficient mechanisms. After the first 30 months of execution, the project has achieved significant milestones including the development of active RF-based sensors for non-invasive bone density monitoring, implementation of secure body area network with advanced cybersecurity mechanisms, creation of prototype mobile application for patient-centred care, and establishment of a comprehensive system architecture that encompasses telemonitoring and telerehabilitation functionalities. The consortium's interdisciplinary approach combines expertise from five leading European institutions spanning academia and industry, fostering knowledge transfer and innovation through a structured secondment program that has facilitated cross-sector collaboration and skills development. This research contributes to the advancement of digital health technologies by providing evidence-based solutions that could save hundreds of millions of euros in annual healthcare costs through reduced hospital stays and readmissions, while supporting personalized at-home guidance that enhances solution adoption and reduces caregiver burden. The project's outcomes establish a foundation for scalable, multidisciplinary bone fracture care with broad benefits for Europe's ageing population and demonstrate the potential for mobile applications in healthcare to address pressing societal challenges.

Keywords: Bone fracture monitoring; Cybersecurity; eHealth; Internet of Things (IoT); RF-based sensing; Telerehabilitation

1. Introduction

The ROBUST research and innovation project emerges as a direct response to one of the most pressing challenges facing European healthcare systems, which is the intersection of an ageing population and the growing burden of musculoskeletal disorders. By 2050, one in four Europeans will be 65 or older, placing unprecedented strain on pension systems and healthcare budgets¹. Within this demographic shift, osteoporosis stands as a particularly severe threat, causing over 3.2 million leg and hip fractures annually among individuals aged 50 and above, with up to 10% developing into non-unions that result in prolonged immobility, repeated hospital visits, and escalating healthcare costs²**Error! Reference source not found.**

Musculoskeletal disorders and diseases represent the most expensive disease category and impose the highest burden on health and social services. Traditional approaches to fracture healing assessment rely heavily on X-rays, which only reveal the quantity of callus formation without providing insights into its quality, making them insufficient for determining fracture severity and difficult to correlate with estimates of bone reunion due to callus formation patterns[1]. This limitation in current diagnostic capabilities has created a significant gap in the provision of personalized, evidence-based rehabilitation protocols.

The European Union has recognized digital innovation as a critical pathway to containing healthcare spending while promoting healthy ageing³. ROBUST addresses this strategic priority by developing a comprehensive eHealth solution that leverages cutting-edge technologies including sensing exploiting radiofrequency (RF) signals, Internet of Things (IoT) infrastructure, artificial intelligence (AI), and machine learning (ML) to create a paradigm shift in bone fracture care. The project's approach transcends traditional telerehabilitation platforms by integrating biomarkers and dynamic analysis capabilities that enable the regulation of exercise intensity according to the patient's specific healing level.

The project consortium represents a carefully orchestrated collaboration between academic excellence and industrial innovation, bringing together five leading European institutions distributed across the continent from Greece in the east to Portugal in the west, encompassing England and Spain. This geographic and institutional diversity includes three academic partners - Instituto de Telecomunicações (IT) in Portugal, the University of Bradford (BRAD) in the United Kingdom, and the University of Patras (UPAT) in Greece - alongside two innovative small and medium enterprises (SMEs): PDM&FC in Portugal and Evotel in Spain⁴. This composition ensures comprehensive coverage of the value chain for telerehabilitation services, spanning from sensor and application development to system integration, implementation, and market deployment.

The ROBUST project's innovation lies in its holistic approach to addressing the technical, social, and economic challenges associated with bone fracture rehabilitation. Unlike existing solutions that merely provide exercise assessment through simple visual user interfaces without clinical validation, ROBUST introduces intelligent systems capable of linking exercise intensity to the patient's healing level while incorporating communication elements that enable healthcare professionals to provide prompt, personalized feedback. This comprehensive approach positions the project to deliver significant economic impact through reduced healthcare costs and improved patient outcomes while contributing to the development of next-generation digital health architectures.

2. Research Objectives and Innovation Framework

The ROBUST project operates within a comprehensive framework of three overarching General Innovation Objectives (GOs) that collectively address the multifaceted challenges of modern healthcare delivery for bone fracture rehabilitation. These innovation objectives are supported by seven specific Research Objectives (ROs) that provide the technical and methodological foundation for achieving

¹ <https://www.un.org/en/global-issues/ageing>

² <https://www.osteoporosis.foundation/facts-statistics/key-statistic-for-europe>

³ <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52012DC0083>

⁴ <http://he-robust.eu/index.html>

breakthrough innovations in eHealth technologies. The following subsections summarize these key ROBUST objectives.

2.1. General Innovation Objectives

These objectives represent the foundational pillars of the project's innovation strategy, designed to create a paradigm shift from traditional fracture care models to intelligent, connected eHealth solutions, namely supporting personalized at-home guidance that enhances solution adoption and reduces caregiver burden.

2.1.1. GO1 – Development of a Customised Body Area Network (BAN)

The development of a customised BAN represents the foundation of the ROBUST technological architecture, encompassing the creation of sensors of different types connected to a cloud-based platform, which can enable further mobile applications in the healthcare sector. This objective involves developing wireless wearable apparatus designed to enable patients with complex fracture focus in stable condition to complete exercises specifically defined for out-of-hospital monitoring and follow-up. The integration encompasses all relevant aspects for monitoring patients' fracture conditions and healing progress, including connectivity with social networks for interaction with patients' relatives and primary care providers. After 30 months of project execution, significant progress has been achieved, though the BAN does not yet include RF-based sensors, which remain in active development.

2.1.2. GO2 – Implementation of a Secure ICT Platform

This objective focuses on building a layered Information and Communication Technology (ICT) stack that spans from on-device preprocessing and encrypted links to cloud middleware and mobile web applications, while ensuring compliance with the General Data Protection Regulation (GDPR) and medical device regulations, namely through the system and user requirements that have been identified for the ROBUST system development. In this respect, the secure ICT platform developed in ROBUST integrates a layered approach to data protection, embedding GDPR compliance and medical device regulation adherence across its architecture. This is achieved by explicitly defining and implementing technical and organizational security and privacy requirements, i.e., including encryption, authentication, access controls, and privacy-preserving data management, within all relevant system components. This objective has progressed significantly since the start of the project, with requirements continuing to be refined and iterated based on technological developments and user feedback. The platform's architecture encompasses different layers including hardware components such as sensors, local software (SW) for preprocessing data and data cleaning, middleware to ensure interoperability, IoT management, scaling and control from local gateways to the cloud platform where gathered data is processed and analysed through cloud-deployed SW.

2.1.3. GO3 – Validation of Mobile Applications in Healthcare

GO3 aims to demonstrate the ability of mobile applications in the healthcare sector to contribute to undertaking societal challenges through a representative use case. This objective represents the most complex and long-term goal since actual validation is only possible after full implementation, end-to-end (E2E) integration and testing. The validation encompasses the full telemonitoring and telerehabilitation patient-to-cloud-to-patient cycles, including bone density measurements via RF-based sensors and limb movements and dynamics via inertial sensors, which are aggregated on mobile devices and transmitted to the cloud through the developed ICT stack for analysis using both individual and population models.

2.2. Specific Research Objectives and Technical Innovation

The seven specific research objectives provide the technical roadmap for achieving the project's ambitious goals, with each RO contributing essential components to the integrated ROBUST platform. These research objectives collectively address the technical, methodological, and validation challenges necessary to create a comprehensive eHealth platform that can revolutionize bone fracture rehabilitation through intelligent, adaptive, and secure remote monitoring capabilities.

2.2.1. RO1 – Technical, Legal and Social Requirements Identification

This objective focuses on comprehensive end-user driven approaches that consider existing rehabilitation programs and define appropriate interactions between users (patients and professionals) and the proposed system. This objective has been achieved through the definition of the ROBUST system reference architecture and evaluation of technical, legal, social, and ethical requirements. This requirements identification process incorporates surveys targeting both healthcare professionals and patients, developed with appropriate ethics clearance procedures.

2.2.2. RO2 – Implementation of Reduced-Size UWB Flexible Sensors

RO2 addresses the development of Ultra-Wideband (UWB) flexible sensors optimized for use on high-absorbable human tissues. The project has already achieved substantial progress in sensor electronics system modelling and feeding network development. The sensors employ reconfigurable spectrum techniques over small sensor arrays to enable operation of many array elements in a small surface area, with signals processed to reconstruct 2D images of fractured bones using Delay-And-Sum (DAS) and Delay-Multiply-And-Sum (DMAS) algorithms combined with rotation subtraction techniques.

2.2.3. RO3 – RF-based Sensing Signal Processing

This RO encompasses the development of advanced signal processing algorithms essential for extracting meaningful information from RF sensor data. This objective involves implementing sophisticated SW solutions for noise filtering, feature extraction, classification, and visualization capabilities. The signal processing chain incorporates ML techniques, time-series analysis, and data fusion methodologies to enhance the accuracy and reliability of bone healing assessment.

2.2.4. RO4 – Intelligent Bone Healing Assessment

This objective represents one of the most innovative aspects of the project, focusing on developing functions that determine rehabilitation exercise intensity based on the fractured bone healing index. This objective depends on the completion of sensor development and signal processing algorithms. The intelligent assessment system will analyse multidisciplinary techniques in ML, signal processing, feature selection, time-series analysis, and data fusion to provide personalized rehabilitation recommendations.

2.2.5. RO5 – Design of Secure Body Area Network (BAN)

The design of ROBUST's secure BAN involves developing integrated adaptive security and privacy frameworks including aggregator, gateway, and mobile application user interface components. The project has achieved substantial progress in secure BAN design and mobile application development. The smartphone-based aggregator implements application programming interfaces (APIs) for inertial sensor data ingestion with local preprocessing capabilities and secure cloud upload functionality.

2.2.6. RO6 – Development and Integration of Complete IoT-based Secure eHealth System

RO6 encompasses the comprehensive integration of all ROBUST components into a cohesive platform. This objective is tightly linked to tasks that only initiate in the second half of the project, focusing on the complete implementation of patient-to-cloud-to-patient cycles. The integration encompasses telemonitoring and telerehabilitation functionalities, including bone density measurements via RF-based sensors and limb movements via inertial sensors.

2.2.7. RO7 – End-user Driven Demonstration and Validation

This final objective aims to validate the complete ROBUST system through eventual clinical testing and user evaluation. This objective requires complete E2E orchestration and testing. The validation will encompass healing times, non-union rates, patient satisfaction, and cost-effectiveness compared to traditional rehabilitation approaches, providing evidence for regulatory approval and clinical adoption.

2.3. Innovation Beyond State-of-the-Art

The ROBUST project's innovation extends significantly beyond current state-of-the-art approaches in several critical dimensions. The current electromagnetic approaches for tissue characterization are constrained by limited understanding of complex permittivity responses of various tissue types. ROBUST addresses this limitation through innovative methods for determining variations in relative permittivity of

scattered waves in thin layers, combined with multi-element tomography to improve spatial localization of tissue layers by incorporating highly decoupled sensors in small surface areas[2].

The project's Bone Mineral Density (BMD) sensing approach based on reconfigurable small microwave sensors represents a significant advancement over traditional imaging methods[3]-[5]. Unlike conventional approaches that emit harmful radiation, ROBUST's sensors enable continuous diagnosis without adverse effects, benefiting elderly patients, pregnant women, and children. The technology also accommodates patients with metallic implants who cannot undergo magnetic resonance imaging (MRI) scans due to strong magnetic field exposure. Once fully commercialized, this system is expected to be the most cost-effective imaging solution on the market, with particular relevance for developing countries.

Comparative analysis with existing solutions suggests that the RF-based sensing approach being developed in ROBUST is expected to offer superior performance across multiple parameters, as indicated in Table 1 below. While traditional medical imaging (MI) methods such as MRI[6], CT Scan[1], and X-Ray[1], as well as DEXA[6], and Ultrasound[7], require lengthy procedures, high costs, contrast agents, ionizing radiation exposure, and lack real-time monitoring capabilities, ROBUST offers short examination times, very low costs, no contrast agents, no ionizing radiation, wearable functionality, medium resolution, real-time monitoring, and high data element capacity. This comprehensive advantage positions ROBUST as a potential transformative technology in medical imaging and rehabilitation monitoring.

Table 1. Comparative analysis of fractured bone sensing technologies

Study	MRI[6]	DEXA[6]	CT Scan[1]	X-Ray[1]	Ultrasound[7]	ROBUST
Target	MI	BMD	MI	MI	Med. ultrasonography	BMD
Time	Very Long	Long	Long	Medium	Medium	Short
Cost	Very High	High	High	Low	Low	Very Low
Personalization programme	--	--	--	--	---	Yes
Contrast agent	Yes	No	No	No	No	No
Ionising radiation	Yes	Yes	Yes	Yes	No	No
Wearable	No	No	No	No	No	Yes
Dosage	High	High	High	Medium	No	No
Resolution	Very High	High	High	High	Low	Medium
Real time monitoring	No	No	No	No	No	Yes
No. of data elements	No	No	No	No	No	High

3. Technological Architecture and System Development

The ROBUST project's technological architecture represents a sophisticated integration of multiple cutting-edge technologies designed to create a comprehensive eHealth platform for bone fracture rehabilitation. The system architecture encompasses five main layers, i.e., RF-based sensing hardware, local preprocessing SW, secure wireless networking, cloud-based analytics, and user interface applications, as illustrated in Figure 1, where the main components of the architecture are depicted. These include RF-based and inertial wearable sensors, a smart mobile device serving as data aggregator and gateway, cloud infrastructure for secure data management and AI-driven analytics, and user-friendly SW applications delivering real-time feedback to patients, authorized assisting relatives, informal carers (via mobile apps), and clinicians (via computer-based dashboards). This multi-layered approach ensures optimal performance, security, and scalability while maintaining energy efficiency and user-centric design principles.

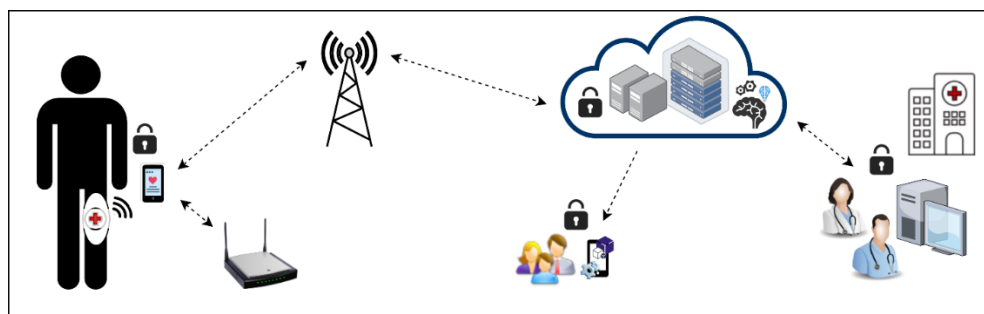


Figure 1. ROBUST platform architecture

3.1. RF-Based Sensing Technology Development

The cornerstone of ROBUST's technological innovation lies in its advanced RF-based sensing capabilities, which have undergone significant development during the first 30 months of the project, building upon previous works[8][9]. The project has successfully transitioned from passive to active RF sensing systems, incorporating varactor diodes to enable dynamic frequency tuning that accommodates the varying dielectric properties of biological tissues throughout the rehabilitation process. This modification allows sensors to operate across a wider frequency range (1-8 GHz), ensuring optimal performance in detecting subtle changes in bone density, fracture size, and hematoma levels.

The proposed active sensor design features dual-frequency operation configurations - one operating from 1-3 GHz and another from 3-8 GHz - providing comprehensive insights into fracture characteristics and healing progression. The sensors incorporate several critical components including copper annealed patches and ground planes for high conductivity and minimal energy loss, FR-4 lossy substrates for mechanical support and frequency stability, varactor diodes for dynamic frequency tuning, capacitors for power stabilization and noise filtering, and microcontrollers for automated data processing and real-time analysis[10].

Extensive research has demonstrated the sensors' superior performance compared to existing solutions across multiple medical applications. The RF sensors have achieved 89% accuracy in detecting changes in bone density during healing, 90% correlation with clinical markers in wound healing monitoring, and 85% accuracy in hydration level detection during physical activity trials. These performance metrics significantly exceed those of passive sensor technologies and establish ROBUST's sensing platform as a leader in precision healthcare monitoring.

The integration of RF sensors with IoT and AI platforms enhances their capabilities for remote patient monitoring and predictive healthcare applications. The sensors employ sophisticated signal processing techniques including Delay-And-Sum (DAS) and Delay-Multiply-And-Sum (DMAS) algorithms combined with rotation subtraction methods to reconstruct 2D images of fractured bones. This signal processing chain incorporates preprocessing and anomaly detection routines that ensure reliable data quality and accurate clinical interpretation[11].

3.2. Secure IoT Platform and Cybersecurity Framework

The ROBUST project has implemented comprehensive cybersecurity schemes and mechanisms that address the critical security challenges inherent in IoT-based healthcare systems. The platform incorporates multiple layers of security including authentication, authorization, encryption, privacy preservation, and intrusion detection capabilities designed specifically for resource-constrained wearable devices. The security framework employs low-complexity cryptography to minimize power consumption and latency overhead while maintaining robust protection against contemporary cybersecurity threats.

3.2.1. Wireless Technology Integration

Wireless technology integration forms a critical component of the secure IoT platform, with careful selection of communication protocols based on energy efficiency, security capabilities, and application requirements. The project primarily utilizes Wi-Fi connectivity for home-based patient monitoring, as patients recovering from bone fractures typically remain at home and rely on widely available Wi-Fi infrastructure rather than mobile networks. However, the system architecture also incorporates Bluetooth Low Energy (BLE) for sensor communication, offering very high energy efficiency with typical current consumption of 5-15 mA during transmission and 1-10 μ A in sleep mode, enabling battery life extending from months to years.

3.2.2. Cloud Security Architecture

Cloud security architecture implements advanced threat protection mechanisms addressing the main security challenges in cloud environments including data breaches, account hijacking, insider threats, and shared technology vulnerabilities. The platform employs pseudonym-based authentication systems and dedicated intrusion detection capabilities to mitigate risks associated with cybersecurity threats. Compliance with regulatory frameworks including GDPR, Health Insurance Portability and Accountability Act (HIPAA), and Food and Drug Administration (FDA) guidelines ensures that the

system meets international standards for health data protection and medical device safety. Building on these foundations, the ROBUST system ensures adherence to such regulations and guidelines, namely by integrating strong data encryption, granular role-based access controls, traceable activity logs, and formal risk management throughout system development and operation. Secure SW development practices, continuous validation against regulatory requirements, and detailed technical documentation further support ongoing compliance with evolving standards for health data confidentiality, integrity, and safety.

3.2.3. Energy Efficiency Optimization

Energy efficiency optimization represents a fundamental design principle throughout the ROBUST platform, with optimization techniques including power management strategies, network protocol optimization, data transmission strategies, and sleep mode duty cycling. The system implements context-aware caching capabilities that postpone transmission when network conditions are unfavourable, optimizing energy consumption while maintaining data integrity and system responsiveness. These energy efficiency measures are critical for ensuring long-term wearability and user acceptance of the sensing devices.

3.3. Mobile Application Development and User Interface Design

The ROBUST mobile application development represents a significant achievement in patient-centred eHealth design, incorporating comprehensive functionality for data visualization, user interaction, and clinical decision support. The smartphone-based aggregator implements advanced APIs developed for ingesting inertial sensor streams while performing preprocessing locally before secure upload to the cloud infrastructure. This edge computing approach reduces bandwidth requirements, improves response times, and enhances privacy protection by minimizing raw data transmission.

3.3.1. User Interface Design Principles

User interface design principles follow established eHealth usability guidelines, incorporating dashboards for visualizing acquired sensing data with role-based access controls and privacy settings embedded directly into the interface. The mobile application serves dual roles as both an aggregator collecting sensor data and a gateway facilitating secure communication with cloud services. Early test versions of the ROBUST mobile application demonstrate functional prototypes with comprehensive data visualization capabilities designed for both testing and clinical deployment scenarios.

3.3.2. Clinical Decision Support Integration

Clinical decision support integration enables the mobile application to provide real-time feedback to patients based on cloud-based analysis of their rehabilitation progress. The system analyses bone density measurements via RF-based sensors and limb movements via inertial sensors, processing this information through machine learning models that consider both individual patient characteristics and population-based recovery patterns. This analysis generates tailored feedback in the form of notifications, audio cues, and visual indicators displayed through the mobile application's user interface, enabling patients to adjust their loading effort and exercise frequency to optimize recovery outcomes.

3.3.3. Interoperability and Scalability

Interoperability and scalability considerations ensure that the mobile application architecture can accommodate future enhancements and integration with other healthcare systems. The application incorporates standardized data formats and communication protocols that facilitate integration with existing clinical workflows and electronic health record systems. This design approach supports the project's objective of creating an open reference platform for telerehabilitation that can be adapted and extended by third-party developers and healthcare organizations.

3.4. Cloud-Based Analytics and AI Integration

The cloud-based analytics platform represents the computational heart of the ROBUST system, incorporating advanced machine learning and artificial intelligence techniques for bone healing assessment and rehabilitation optimization. The platform processes complex sensor data streams in real-time, applying sophisticated algorithms for pattern recognition, anomaly detection, and predictive

analytics that enable personalized rehabilitation recommendations. This cloud infrastructure supports scalable data storage, analysis, and visualization capabilities designed to accommodate large populations of patients while maintaining individual-level precision in clinical recommendations.

3.4.1. Machine Learning Model Development

Machine learning model development incorporates multidisciplinary approaches combining signal processing, feature selection, time-series analysis, and data fusion techniques to extract meaningful insights from RF sensor data and inertial measurements. The AI models consider both individual patient characteristics and population-based recovery patterns to generate personalized rehabilitation protocols that adapt dynamically as healing progresses. This adaptive approach ensures that exercise intensity and frequency recommendations remain optimal throughout the entire rehabilitation period, maximizing healing outcomes while minimizing the risk of re-injury.

3.4.2. Data Integration and Processing Pipeline

Data integration and processing pipeline manages the complex workflow of sensor data ingestion, preprocessing, analysis, and clinical decision support generation. The cloud platform implements robust data management practices including automated backup systems, disaster recovery protocols, and compliance with healthcare data protection regulations. The processing pipeline incorporates quality assurance mechanisms that validate sensor data integrity, identify potential anomalies, and ensure that clinical recommendations are based on reliable measurements.

3.4.3. Predictive Analytics and Clinical Intelligence

Predictive analytics and clinical intelligence enable the system to anticipate potential complications, optimize rehabilitation timelines, and provide evidence-based guidance for clinical decision-making. The analytics platform generates comprehensive reports for healthcare professionals, including healing progress visualizations, exercise compliance metrics, and predictive assessments of recovery trajectories. This clinical intelligence supports patient self-management and professional healthcare delivery, creating a comprehensive ecosystem for fracture rehabilitation care.

4. Impact and Implications for Future Healthcare

The ROBUST project's impact extends far beyond its immediate technical achievements, positioning it as a catalyst for transformative change in European healthcare delivery systems and global eHealth innovation. The project addresses critical societal challenges associated with population ageing, healthcare cost containment, and the need for personalized medical care through technological innovation that demonstrates measurable benefits for patients, healthcare providers, and society as a whole. The comprehensive approach to bone fracture rehabilitation represents a paradigm shift from reactive treatment models to proactive, data-driven care that optimizes healing outcomes while reducing economic burden on healthcare systems.

4.1. Economic Impact and Healthcare Cost Reduction

The economic impact that ROBUST's outcomes can produce, namely with respect to healthcare cost reduction are summarised as follows.

4.1.1. Healthcare Cost Savings

Healthcare cost savings represent one of the most significant potential impacts of ROBUST technology deployment, with projections indicating hundreds of millions of euros in annual savings through reduced hospital stays and readmissions. The project's home-based monitoring and rehabilitation capabilities directly address the economic burden of musculoskeletal disorders, which represent the most expensive disease category and highest burden on health and social services in Europe. By enabling early detection of complications, optimizing rehabilitation protocols, and reducing the need for repeated clinical visits, ROBUST technology can substantially decrease the total cost of fracture care while improving patient outcomes.

4.1.2. Market Transformation and Commercial Opportunities

Market transformation and commercial opportunities emerge from ROBUST's development of the most cost-effective imaging system anticipated for the medical sector, with particular relevance for developing countries where access to expensive traditional imaging technologies is limited. The microwave-based BMD sensors offer painless diagnosis capabilities for patients with metallic implants who cannot undergo MRI scans, expanding the addressable market for bone health monitoring. The project's business model development has identified revenue streams based on pay-per-rehabilitation-episode approaches that share risk with healthcare providers while incentivizing outcome optimization.

4.1.3. Innovation Ecosystem Development

Innovation ecosystem development positions ROBUST as a foundation for broader eHealth industry growth through its open platform architecture and reference implementation approach. The project's contribution to wearable device certification and reimbursement frameworks provides policy-relevant evidence that can inform Digital Europe funding programs and similar initiatives designed to foster scalable eHealth solutions. The public-private consortium model exemplifies best practices for the Marie Skłodowska-Curie Staff Exchanges (MCSA-SE) Horizon Europe action and partnerships that can be replicated across other healthcare technology domains.

4.2. Clinical and Social Impact

The clinical and social impact that ROBUST's outcomes can produce is summarised as follows:

4.2.1. Personalized Healthcare Delivery

Personalized healthcare delivery represents a fundamental advancement enabled by ROBUST's intelligent bone healing assessment capabilities that adapt rehabilitation protocols to individual patient characteristics and healing progress. The system's ability to provide real-time feedback and dynamic adjustment of exercise intensity based on biomarker analysis ensures optimal healing conditions while minimizing the risk of re-injury or prolonged recovery periods. This personalized approach addresses the significant gap in existing telerehabilitation platforms that lack intelligence for linking exercise intensity to individual healing levels.

4.2.2. Patient Empowerment and Autonomous Care

Patient empowerment and autonomous care emerge through ROBUST's patient-centred design that enables individuals to actively participate in their rehabilitation process with confidence and clinical oversight. The mobile application's intuitive interface provides patients with real-time guidance, progress visualization, and direct communication channels with healthcare professionals, reducing anxiety and improving compliance with rehabilitation protocols. This empowerment is particularly valuable for elderly patients who benefit from aging-in-place support that reduces caregiver burden while maintaining clinical supervision[12].

4.2.3. Healthcare System Resilience and Capacity

Healthcare system resilience and capacity benefit from ROBUST's distributed care model that reduces demand on hospital resources while maintaining high-quality clinical outcomes. The system enables healthcare professionals to monitor multiple patients simultaneously through cloud-based dashboards that highlight cases requiring immediate attention while providing automated oversight for patients progressing normally. This scalability is essential for addressing the growing burden of musculoskeletal disorders in an aging population without proportional increases in healthcare infrastructure.

4.2.4. Social Inclusion and Accessibility

Social inclusion and accessibility are enhanced through ROBUST's design considerations for diverse patient populations including elderly individuals, pregnant women, children, and patients with metallic implants who face limitations with traditional imaging approaches. The system's non-ionizing radiation approach and wearable form factor make it accessible to vulnerable populations who require specialized care considerations. The project's multilingual support and cultural adaptation capabilities ensure that benefits extend across diverse European communities.

4.3. Scientific and Technological Contributions

The scientific and technological impact that ROBUST's outcomes are expected to produce is summarised as follows:

4.3.1. Advancement of RF-Based Medical Sensing

Advancement of RF-based medical sensing represents a significant contribution to the scientific understanding of electromagnetic approaches for tissue characterization, addressing current limitations in comprehending complex permittivity responses of various tissue types. ROBUST's innovative methods for determining variations in relative permittivity of scattered waves in thin layers, combined with multi-element tomography approaches, expand the toolkit available for reliable identification of distinct tissue types[13-14]. The project's active sensor technology with varactor-based frequency tuning capabilities establishes new benchmarks for precision, adaptability, and energy efficiency in medical sensing applications.

4.3.2. Integration of AI and IoT in Healthcare

Integration of AI and IoT in healthcare demonstrates sophisticated approaches to combining artificial intelligence, machine learning, and Internet of Things technologies for clinical decision support and predictive healthcare. The project's multidisciplinary approach incorporating signal processing, feature selection, time-series analysis, and data fusion techniques provides a comprehensive framework for developing intelligent healthcare systems that can adapt to complex, dynamic clinical scenarios. These contributions advance the state-of-the-art in precision medicine and personalized healthcare delivery[15-17].

4.3.3. Cybersecurity and Privacy Innovation

Cybersecurity and privacy innovation addresses critical challenges in protecting sensitive healthcare data while enabling real-time monitoring and analysis capabilities[18]. ROBUST's implementation of lightweight cryptography, pseudonym-based authentication, and dedicated intrusion detection systems for resource-constrained wearable devices establishes new standards for healthcare IoT security[19]. The project's compliance with GDPR, HIPAA, and FDA guidelines while maintaining system performance and usability provides a model for future healthcare technology development[20].

4.3.4. Open Science and Knowledge Sharing

Open science and knowledge sharing contribute to the broader research community through comprehensive documentation, open access publication, and collaborative development practices that enable other researchers to build upon ROBUST's innovations. The project's commitment to findable, accessible, interoperable, and reusable (FAIR) data principles and systematic knowledge transfer through secondment programs creates lasting impact beyond the immediate project timeline.

4.4. Policy and Regulatory Implications

The envisaged ROBUST project impact on policy and regulations is summarised as follows:

4.4.1. Digital Health Policy Development

Digital health policy development benefits from ROBUST's evidence-based approach to demonstrating the safety, efficacy, and cost-effectiveness of advanced eHealth technologies in real-world clinical settings. The project's comprehensive evaluation of regulatory compliance requirements across multiple jurisdictions provides valuable insights for policymakers developing frameworks for digital health technology approval and reimbursement. The anticipated cost-effectiveness analyses and hospital savings projections can inform Digital Europe and similar funding programs designed to foster scalable eHealth innovation.

4.4.2. Medical Device Regulation and Standards

Medical device regulation and standards are informed by ROBUST's systematic approach to addressing relevant guidelines, GDPR compliance, and medical device safety requirements throughout the technology development process. The project's documentation of regulatory pathways for RF-based medical sensors, AI-enabled clinical decision support systems, and IoT-based healthcare platforms

provides guidance for future innovation projects navigating complex approval processes. This regulatory intelligence contributes to the development of harmonized standards that can accelerate the deployment of beneficial healthcare technologies.

4.4.3. Healthcare Technology Assessment and Adoption

Healthcare technology assessment and adoption frameworks benefit from ROBUST's comprehensive approach to evaluating technology impact across multiple dimensions including clinical outcomes, economic benefits, user satisfaction, and system integration requirements. The project's methodology for assessing healing times, non-union rates, patient satisfaction, and cost-effectiveness provides a model for evidence-based technology adoption decisions. This systematic approach to health technology assessment can inform healthcare policy development and resource allocation decisions across European healthcare systems.

4.4.4. International Cooperation and Innovation Policy

International cooperation and innovation policy are strengthened through ROBUST's demonstration of successful cross-border collaboration, knowledge transfer, and public-private partnership models. The project's MCSA-SE program exemplifies best practices for international research collaboration that can be replicated across other domains and funding programs. The consortium's geographic distribution from east to west across Europe demonstrates the potential for creating sustainable innovation networks that leverage diverse expertise and perspectives.

5. Conclusion

The ROBUST research and innovation project represents a paradigmatic advancement in eHealth solutions for fracture orthopaedic rehabilitation, demonstrating how interdisciplinary collaboration, cutting-edge technology integration, and patient-centred design can address critical challenges in modern healthcare delivery. After 30 months of significant development, the project has established a solid foundation for transforming bone fracture care through innovative RF-based sensing technologies, secure IoT infrastructure, intelligent mobile applications, and cloud-based analytics that enable personalized, evidence-based rehabilitation protocols.

The project's comprehensive approach addresses multiple dimensions of healthcare innovation, from technical excellence in sensor development and cybersecurity implementation to clinical validation and market deployment strategies that ensure sustainable impact beyond the research phase. The consortium's successful integration of academic expertise and industrial experience across five European institutions demonstrates the value of international collaboration in tackling complex healthcare challenges that require multidisciplinary solutions.

ROBUST's contributions extend beyond immediate technical achievements to encompass broader implications for healthcare policy, regulatory frameworks, and innovation ecosystems that will continue generating benefits throughout Europe and globally. The project's evidence-based approach to demonstrating cost-effectiveness, clinical efficacy, and user satisfaction provides a model for healthcare technology development that balances innovation with rigorous validation and regulatory compliance.

The remaining 18 months of the ROBUST project will focus on complete system integration, comprehensive clinical validation, and establishment of sustainable pathways for continued innovation and market deployment. The foundation established during the first 30 months positions the consortium to achieve its ambitious objectives while creating lasting impact through technology commercialization, continued research collaboration, and contribution to the broader advancement of digital health solutions.

The ROBUST project exemplifies the potential for European research and innovation programs to generate solutions that address societal challenges while advancing scientific knowledge and fostering international collaboration. As healthcare systems worldwide grapple with aging populations, rising costs, and increasing demand for personalized care, ROBUST's innovations provide a roadmap for leveraging technology to create more sustainable, efficient, and patient-centred healthcare delivery models that benefit both individuals and society.

CRedit Author Contribution Statement

Joaquim Bastos: Project Administration, Writing – Original Draft; Raed A. Abd-Alhameed: Conceptualization, Supervision; Evanthia Karavatselou: Conceptualization, Investigation; Jorge Martins: Methodology, Investigation; Valdemar Monteiro: Investigation, Writing – Review & Editing.

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