Original Paper

Economic, Organizational, and Research Impact Evaluation of Introducing Robotic Rehabilitation in a Medium-Sized Hospital: Scenario-Based Comparative Analysis

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Abstract

Background: While the clinical efficacy of robotic rehabilitation is well documented, its widespread adoption is often hindered by uncertainty regarding its organizational and systemic impact. A comprehensive evaluation that integrates economic sustainability with research and innovation potential is currently lacking.

Objective: This study evaluates the economic, organizational, and scientific impact of introducing a robotic rehabilitation unit in a medium-sized hospital, comparing it with standard care through a health technology assessment–based simulation model.

Methods: A comparative scenario-based model was developed to simulate 2 equivalent facilities over a 5-year horizon: a "hybrid" clinic (robotics + conventional therapy) and a standard care clinic. The model uses a "workforce multiplier" framework and evaluates efficiency through the cost per point of clinical outcome (Fugl-Meyer Assessment).

Results: Under the simulation hypothesis, robotic integration allows for a 16.1% reduction in cost per patient and an increase in workforce efficiency. Our scenario-based analysis suggests that robotic-assisted rehabilitation units can achieve favorable cost-effectiveness profiles compared with standard manual care, provided that patient throughput remains high. However, robotic systems do not replace the necessity of careful capital budgeting and workflow reorganization.

Conclusions: Robotic rehabilitation should be appraised not merely as a technological cost, but as a multiplier of organizational capacity and a driver of digital innovation. Institutional decision-makers should view robotic adoption as a strategic operational shift rather than a stand-alone guaranteed cost-reduction tool.

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KEYWORDS

cost-effectiveness; health technology assessment; hospital management; robotic rehabilitation; scenario analysis; health systems engineering

Introduction

Neurological and orthopedic conditions represent leading causes of long-term disability worldwide and account for a large proportion of rehabilitation demand in hospital settings [1]. Poststroke rehabilitation plays a critical role in promoting functional recovery and reducing long-term dependency, with evidence supporting the importance of early, intensive, and task-specific therapy [2,3]. Conventional rehabilitation relies heavily on one-to-one therapist-patient interaction and manual guidance. This model presents intrinsic limitations in terms of achievable treatment intensity, reproducibility of exercises, and scalability with increasing patient volumes [4-6]. High-intensity and repetitive motor training is often constrained by therapist fatigue, time availability, and organizational limits [7,8]. From an organizational perspective, rehabilitation departments face growing pressure to increase performance while maintaining quality of care, in a context of constrained budgets and

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workforce shortages [9]. Long waiting times, heterogeneous treatment protocols, and limited access to high-dose therapy for patients with severe impairments remain common challenges [2,6]. These factors have stimulated interest in technological solutions capable of supporting therapists and enhancing the efficiency of rehabilitation delivery.

Robotic rehabilitation systems have been developed to deliver high-intensity, repetitive, and quantifiable motor training. Clinical studies have reported improvements in motor function, particularly in patients who have had a stroke, when robotic therapy is used to support conventional treatment [5,8,10]. There is evidence that robotic therapy has a small, statistically significant positive effect [11] or no improvement compared with standard therapy [12]. Meta-analyses suggest that robotic-assisted therapy can increase the amount of practice delivered per session when appropriately integrated into multidisciplinary rehabilitation programs [8,13]. Robotic systems offer potential organizational advantages, including the possibility of automating treatments, reducing therapist physical load, and enabling more standardized and monitored therapy protocols [14,15]. The automatic recording of kinematic and kinetic data further opens opportunities for quantitative outcome assessment and longitudinal monitoring of patient recovery.

However, adoption in routine hospital practice remains limited. High acquisition costs, maintenance expenses, and the need for dedicated infrastructure represent major economic barriers [16-18]. Additional obstacles include the need for specialized staff training, integration into existing clinical workflows, and uncertainty regarding reimbursement mechanisms and long-term sustainability [19,20]. As a result, robotic rehabilitation is often confined to research-oriented centers or highly specialized units rather than being systematically implemented at the hospital level. The majority of published studies on robotic rehabilitation focus on clinical efficacy and motor outcomes, typically through randomized controlled trials or controlled cohort studies [5,8,10]. They provide limited insight into the broader consequences of technology adoption for hospital organization. Only a small number of investigations have addressed economic aspects, often using cost-effectiveness frameworks applied to specific devices or short time horizons [16,21]. Even fewer studies have examined the systemic impact of introducing robotic rehabilitation units in real hospital contexts, considering patient throughput, staff workload, and infrastructural requirements simultaneously [17,19]. Moreover, the potential research and innovation benefits of robotic rehabilitation—such as the generation of structured clinical datasets and the attraction of academic and industrial collaborations—are rarely included in formal evaluations. These dimensions are increasingly relevant for medium-sized hospitals seeking to strengthen their role within clinical research networks and innovation ecosystems [22]. Finally, few studies adopt a comparative scenario-based approach contrasting a hospital implementing robotic rehabilitation with an equivalent hospital providing only standard care. This limits the ability of decision-makers to assess the opportunity cost and evaluate alternative organizational strategies under realistic operational constraints.

This study addresses an evidence gap in the evaluation of rehabilitation technologies by focusing on organizational and economic consequences rather than clinical efficacy alone. The aim is to evaluate the organizational, clinical, economic, and scientific impact of introducing a robotic rehabilitation unit in a medium-sized hospital through a scenario-based comparative model. Two equivalent hospital scenarios are simulated over a multiyear time horizon: clinic A, implementing robotic-assisted rehabilitation alongside conventional therapy, and clinic B, relying exclusively on standard rehabilitation care. This approach aims to provide a multidimensional assessment of robotic rehabilitation adoption at the hospital level.

Methods

Study Design

This study adopted a scenario-based simulation design to evaluate the economic, organizational, and research impact of introducing a robotic rehabilitation unit in a medium-sized hospital. Two hypothetical but structurally equivalent hospitals were modeled and compared over a multiyear time horizon: clinic A, implementing a novel robotic rehabilitation unit integrated within standard rehabilitation services; and clinic B, providing conventional rehabilitation care only. Both scenarios were assumed to operate within the same regional health care system and under identical regulatory and reimbursement frameworks. The model was developed from the hospital perspective, focusing on direct capital and operating costs, organizational processes, and patient throughput. The time horizon of the analysis was set at 5 years to capture both initial investment costs and medium-term operational dynamics, including device depreciation and stabilization of clinical workflows. The model structure combined elements of budget impact analysis and organizational simulation, with baseline assumptions and sensitivity analyses to explore parameter uncertainty. No individual patient-level simulation was performed; instead, average patient profiles and treatment pathways were modeled based on typical caseloads in neurological and orthopedic rehabilitation units.

Description of the 2 Scenarios

Baseline Hospital Characteristics

The reference setting was a medium-sized general hospital with an inpatient and outpatient rehabilitation department. The modeled hospital was assumed to manage a mixed caseload of neurological and orthopedic patients, primarily including stroke, traumatic brain injury, spinal cord injury (in the subacute phase), and postsurgical orthopedic conditions, and others. Baseline characteristics included a stable annual volume of patients undergoing rehabilitation, including inpatients and a comparable number of external patients; standard multidisciplinary staff composed of physiotherapists, physicians, nurses, and occupational therapists; and conventional therapy pathways based on individualized sessions of manual therapy and task-oriented exercises. Average treatment duration, number of sessions per patient, and staffing ratios were derived from or inspired by published benchmarks and typical organizational patterns observed in European hospital rehabilitation units.

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Clinic A Scenario: A Novel Robotic Rehabilitation Unit

In scenario A, the hospital was assumed to introduce a robotic rehabilitation unit integrated into the existing rehabilitation department. The unit included robotic devices for upper-limb rehabilitation, selected to represent commonly adopted clinical platforms for poststroke and orthopedic motor recovery. The robotic unit was characterized by: (1) a predefined number of robotic systems for the upper-limb extremities (in this model, 2 upper-limb robots), (2) dedicated therapy spaces adapted to accommodate robotic equipment and ensure patient safety, (3) a core team of trained physiotherapists responsible for delivering robotic-assisted sessions, and (4) support from a clinical engineer or technical specialist for maintenance and troubleshooting. Robotic therapy was modeled as being delivered in addition to conventional rehabilitation, partially replacing manual therapy time for selected patient groups. Patients eligible for robotic therapy were assumed to be those with moderate to severe motor impairment requiring high-intensity repetitive training or selected patients deemed fit for medical robotics by physicians. The robotic unit was also assumed to potentially generate structured clinical datasets that could be used for observational studies and applied research projects, thereby increasing the hospital's research capacity.

Clinic B Scenario: Standard Rehabilitation

Scenario B represented a hospital providing only conventional rehabilitation services, without robotic devices. Therapy consisted of manual and task-oriented exercises delivered by physiotherapists in individual or small-group sessions. The available therapy time was assumed to be identical to that in scenario A at baseline. However, treatment intensity and throughput were constrained by therapist availability and physical workload. No automated collection of kinematic data or technology-driven standardization of therapy protocols was assumed in this scenario. Research activity related to rehabilitation was limited to traditional clinical observation, administration of clinical scales, and sporadic data collection, without access to high-frequency quantitative motor measurements.

Model Hypothesis

Table 1 summarizes the quantitative hypotheses and assumptions made for the model. Model parameters were derived from the following main sources: published literature on robotic rehabilitation effectiveness, costs, and organizational use; publicly available data on patient volumes in comparable European rehabilitation hospitals; price ranges reported by manufacturers, brochures, and clinical engineering reports; and feedback from clinics operating in the field.

When direct data were unavailable, conservative assumptions were adopted and tested through sensitivity analysis. All assumptions were explicitly reported in the model description.

Robotic-assisted rehabilitation was assumed to increase the achievable intensity of therapy by enabling longer or more frequent sessions without a proportional increase in therapist physical workload. Functional effectiveness values (Fugl-Meyer Assessment [FMA] motor score improvement) were derived from published randomized trials and meta-analyses comparing robotic-assisted and conventional rehabilitation. A comparative therapy quality framework was derived from the literature to characterize differences between robotic-assisted and standard rehabilitation. Evidence indicates that robotic rehabilitation may provide superior intrinsic therapeutic mechanisms through ad hoc assist-as-needed mechanisms but allows the delivery of a higher and more standardized therapy dose under comparable staffing conditions [5,8,10,11]. These dimensions were therefore used to qualitatively compare the expected quality of therapy between scenarios. Quantitative indicators of rehabilitation effectiveness were derived from published randomized trials and meta-analyses comparing robotic-assisted and conventional therapy. Reported ranges for repetitions per session, therapy frequency, and functional outcome improvements (FMA and activities of daily life [ADL] scales) were extracted and used to estimate cost-normalized effectiveness metrics. These values were combined with model-based cost estimates to compute cost-normalized indicators. This approach aimed to link therapy effectiveness and economic outcomes without assuming superior intrinsic efficacy of robotic rehabilitation but rather by reflecting higher delivered therapy dose and access under comparable staff conditions.

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Table 1. Hypotheses and assumptions for the model.

Parameter/assumption	Scenario A	Scenario B	Source/assumption
Number of robots available, n	2	0	Fundamental model assumption
Daily operating time per robot (hours)	8	N/A[a]	Standard hospital working hours per day
Average duration per robotic session (minutes)	30	30	Clinical literature/robotic physiotherapy protocol [23]
Robot use rate, %	100	N/A	Model assumption, subject to sensitivity analysis
Daily therapist working time (hours)	8	8	Standard hospital working hours
Duration per standard occupational therapy session (minutes)	30	30	Clinical literature/hospital protocols [23]
Hourly cost per therapist (€)[b]	30	30	Real cost/hospital contracts
Robot purchase cost (unit cost; €)	200,000	0	Manufacturer quote/literature
Robot installation cost (€)	100,000	0	Estimated from manufacturer quote, includes structural costs
Robot maintenance cost (€)	50,000	0	Estimated from literature [24]
Robot depreciation (years)	5	N/A	Standard accounting practice
Number of patients treated per month, n	80 (40 inpatients, 40 external patients)	60 (40 inpatients, 20 external patients)	Hospital data/realistic estimate
Number of sessions per patient (1 month), n	13	13	Clinical literature/rehabilitation protocols
Average clinical improvement per patient (FMA[c]), points	+5/+7	+3/+5	Clinical trial/reference [10,25,26]
Treatment cycle duration (months), n	1	1	Standard clinical protocol
Annual robot maintenance cost per robot (€)	5000	N/A	Manufacturer quote/literature
Consumables cost per session per patient (€)	5	5	Model estimate/clinical data [24]
Maximum robot capacity, %	100	N/A	Model assumption
Percentage of sessions lost (absence/failure), %	10	0	Hospital historical data/assumption [27]
Number of robot days available per month, n	20	N/A	Working days per months
Maximum number of patients administered with robot therapy per month, n	45	N/A	Derived from model
Corresponding full-time therapists needed (FTE[d])	2.34	2.44	Derived from model
Reimbursement per session (€)	33.75	33.75	Reasonable model assumption
External patients included	Yes	Yes	Model assumption
Robot therapist supervises multiple patients, n	2	N/A	Model assumption/clinical practice [10,11,28,29]
Maximum number of patients administered by 1 occupational therapy therapist during a session, n	1	1	Model assumption
Maximum robotic sessions per day	Limited by robot capacity and hours	Limited by robot capacity and hours	Derived from model
Break-even calculation	Based on cumulative direct costs only	Based on cumulative direct costs only	Model assumption

[a]N/A: not applicable.

[b]€1=US $1.12 as of October 26, 2026.

[c]FMA: Fugl-Meyer Assessment.

[d]FTE: full-time equivalent.

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Clinical and Organizational Assumptions

Other hypotheses for the model include the following assumptions. Klamroth-Marganska et al [23] reported at least 45 minutes per session per week. Based on these data and considering the capabilities of low-functioning patients, we opted for a conservative duration of 30 minutes per session.

Previous studies have reported modest but clinically relevant improvements in upper-limb motor function following robot-assisted or electromechanical rehabilitation, with between-group differences in the FMA of approximately 2 to 3 points reported in controlled trials [10], while systematic reviews have confirmed overall beneficial effects of robot-assisted and electromechanical training on upper-limb function [25]. Moreover, real-world observational data have reported larger pre-post FMA improvements following robot-assisted rehabilitation, in the range of approximately 7 to 11 points depending on the robotic technology used [10,25,26], supporting the plausibility of a moderate improvement in motor outcomes under intensive robotic rehabilitation scenarios. Based on these data, we chose a realistic, cautious scenario (+5/+7 FMA points with robot, +3/+5 points with standard therapy).

Maximum robot capacity was set to 100%. Since this value might be unrealistic or at least difficult to achieve, sensitivity analysis will also consider lower robot use rates, as well as 10% of sessions being lost.

Auxiliary personnel expenditures—such as initial technology-specific training programs and variations in treatment efficiency linked to individual therapist expertise—were modeled as structural overheads rather than dynamic per-session variables. While onboarding new robotic devices requires initial staff training, these setup costs are typically amortized across institutional operational budgets and do not alter the macrolevel comparative cost-effectiveness between robotic and manual pathways.

Economic parameters related to hardware acquisition, installation, and maintenance were established using aggregated market benchmarks and standardized vendor quotations reflecting commercial upper-limb robotic technologies, ensuring generalizability beyond specific proprietary brand pricing.

Clinical outcomes are reported as aggregate average FMA score improvements across standardized virtual patient cohorts rather than stratified baseline severities, reflecting macrolevel therapeutic efficacy rather than individual patient-level recovery curves. Calculating cumulative annual clinical gains via weighted averages assumes population-level homogeneity, thereby omitting individual response variance and nonlinear recovery profiles typical of heterogeneous clinical cohorts.

Consumable costs per session were modeled using a standardized parity assumption across both pathways. While robotic systems may involve specific component replacements or specialized hygienic accessories, these marginal expenses account for a minimal share of total operational costs compared with labor and capital investments, preserving the structural validity of the cost comparison.

The 5-year analytical horizon focuses strictly on the initial capital amortization cycle. In real-world hospital operations, robotic rehabilitation devices frequently remain functional and heavily used well beyond this initial period, meaning that long-term operational phases often benefit from postamortization efficiency, where capital acquisition costs are fully absorbed. For this reason, no equipment disposal costs were considered. No discount rate was applied to costs or health outcomes over the 5-year time horizon.

We assumed institutional alignment and compliance with workflow reengineering. In clinical practice, successful technology integration depends on overcoming initial staff resistance through adequate training and change management. However, because robotic devices function as clinical support tools designed to reduce physical fatigue and augment supervision capacity rather than displace personnel, organizational integration is structured as a collaborative enhancement of the existing health care team.

Cost Model and Economic Evaluation Framework

Overview

The economic evaluation was conducted from the hospital's perspective over a 5-year time horizon, following the reporting guidance of the Consolidated Health Economic Evaluation Reporting Standards (CHEERS) statement [30]. Multimedia Appendix 1 provides the CHEERS checklist. The model integrates capital, operational, and direct labor expenditures to assess the budget impact and cost-effectiveness of introducing a robotic rehabilitation unit (clinic A) vs standard manual care (clinic B).

Capital and Equipment Costs (Investment Phase)

For clinic A, capital expenditures include the acquisition of 2 upper-limb robotic systems (C_{acq}=€200,000 each; €1=US $1.12 as of October 26, 2026), site installation and structural safety adaptations (C_{inst}=€100,000 total), and long-term maintenance agreements (C_{maint}=€5000 per robot per year, totaling €50,000 over the 5-year horizon). Capital costs are annualized using a straight-line depreciation method over a 5-year useful life (L=5 years) with zero residual salvage value:

$$\text{annual depreciation} = \frac{2 \cdot C_{acq} + C_{ins}}{L} + \text{annual maintenance}$$

Clinic B incurs no capital expenditures for robotic technology.

Operating and Personnel Costs (Operational Phase)

Personnel expenditures are modeled dynamically based on the full-time equivalent (FTE) staff required to sustain the annual volume of therapy sessions. The hourly cost per physiotherapist (w) is fixed at €30 per hour based on standard European hospital employment contracts. Total annual personnel cost is computed as:

$$C_{Staff} = FTE_{needed} \cdot \text{annual working hours} \cdot w$$

In clinic A, the model explicitly accounts for the "workforce multiplier" effect, where a 1:2 therapist-to-patient supervision ratio reduces the relative labor input per session compared with the 1:1 manual ratio in clinic B. Supervision ratios are modeled

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as macrolevel operational averages rather than static constraints. While early-stage patients with severe impairment require intensive 1:1 therapist-to-patient attention, the robotic model accommodates progressive skill acquisition, allowing patients with mild to moderate impairments to be managed under optimized multipatient supervision ratios (eg, up to 1:2 or 1:3 during autonomous execution phases). Consequently, the projected efficiency gains reflect an aggregate operational average across the continuum of the rehabilitation cycle rather than a uniform one-size-fits-all ratio.

Consumables and Direct Operational Logistics

Session-specific consumables (such as hygienic interfaces and accessories) are modeled at a flat rate of €5 per session for both scenarios. Administrative overhead and scheduling logistics are assumed to scale proportionally with patient throughput.

$C_{\text{Consumables}}$ = total annual sessions · €5

A uniform reimbursement rate of €33.75 per rehabilitation session was assumed for both clinics, irrespective of inpatient or outpatient status. Annual revenue was calculated as the number of patients treated per month × 12 months × 13 sessions per patient × €33.75 per session. This uniform rate was used as a simplifying assumption for the economic comparison and was not intended to represent setting-specific reimbursement tariffs.

Total Direct Costs and Margins

Total annual direct costs (DCs) for each clinic are calculated as the sum of personnel, technology/depreciation, and consumables (maintenance + consumables). Cost per patient and cost per FMA point gained are evaluated as core value-based metrics to determine economic efficiency.

$\text{DC} = C_{\text{Staff}} + C_{\text{Tech}} + C_{\text{Consumables}}$

Total annual revenue is derived from standard institutional reimbursement rates for outpatient and inpatient rehabilitation cycles. The gross operating margin (earnings before interest, taxes, depreciation, and amortization [EBITDA]) is calculated as:

EBITDA = total annual revenue – DC

Finally, cost per patient and cost per FMA point gained are evaluated as core value-based metrics to determine economic efficiency.

Outcome Model

The outcome model was developed to capture three complementary dimensions: clinical, organizational, and scientific/innovation-related outcomes.

Organizational Outcomes

Organizational outcomes focused on the operational performance of the rehabilitation service and included annual patient throughput, defined as the total number of patients who successfully complete their treatment program within a year. This metric reflects the facility's total capacity and is a driver for amortizing fixed technological costs. Total annual sessions refers to the aggregate number of individual therapy sessions delivered by the department annually. It is determined by the patient volume multiplied by the number of sessions prescribed per clinical protocol. Annual therapy hours represent the total volume of effective treatment time provided to the patient population. Given a standard session duration (eg, 30 minutes), this metric represents the cumulative "dose" of therapy delivered by the unit. Workforce needed (FTE) refers to the number of FTE staff members required to sustain the projected clinical workload. This measure highlights how robotic integration can decouple patient volume from human labor requirements. Productivity (sessions/FTE) is an efficiency ratio representing the average number of therapy sessions managed by 1 full-time therapist per year. It quantifies the "workforce multiplier" effect of technology, showing the increase in output per staff member enabled by robotic-assisted supervision models.

Regarding therapists, hours of therapy (annual therapy hours) represent the total cumulative volume of effective treatment time delivered to the entire patient population over 1 year. This metric is calculated based on the total number of sessions multiplied by the duration of each session. It serves as a measure of the total "therapeutic dose" the facility is capable of providing. FTE needed (workforce needed) indicates the number of FTE therapists required to cover the total annual therapy workload. In the model, it accounts for the different supervision ratios, showing how robotic integration (1:2 ratio) allows a facility to manage higher patient volumes with fewer staff members compared with the manual 1:1 model. Efficiency (therapy hours per FTE) measures the amount of therapy time successfully delivered by each full-time therapist unit per year. It quantifies the operational gain of the robotic unit, demonstrating how technology enables therapists to "produce" more treatment time by supervising multiple automated sessions simultaneously.

Economic Evaluation

Economic evaluation was performed using a combination of total annual revenue, which represents the total revenue generated from rehabilitation services in a year; DCs (staff + tech), which are the sum of personnel costs (physical therapists required to cover therapy hours) and technology costs (depreciation of machines, maintenance, and consumables); and operating margin (EBITDA), which indicates the gross operating margin (revenue – DCs).

Clinical Outcomes (Economically Weighted)

Clinical outcomes were modeled at an aggregate level and included weighted average FMA improvement, which represents the average change in the FMA score—the gold standard for evaluating motor recovery—achieved by patients after a full treatment cycle. It is "weighted" to reflect the specific clinical evidence found in the literature for both robotic-assisted (scenario A) and manual (scenario B) therapies. Annual clinical gain (total FMA points) is a systemic impact metric that quantifies the "total amount of recovery" produced by the department in 1 year. It is calculated by multiplying annual patient throughput by the weighted average FMA improvement. Therapy delivery effectiveness measures the clinical gain achieved relative to the resources invested (eg, FMA points per hour of therapy or per therapist FTE). It evaluates the "quality" of the organizational model, demonstrating how effectively the

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clinical protocol translates staff effort and technological support into measurable patient recovery.

Health Technology Assessment

To provide a comprehensive evaluation of the transition from manual to robotic-assisted therapy, a multidimensional framework based on health technology assessment (HTA [31]) principles was adopted. Beyond clinical efficacy, specific metrics to quantify organizational scalability (eg, staff engagement ratio) and economic sustainability (eg, cost per FMA point gained) were introduced. These parameters allow for a value-based comparison, aligning clinical recovery with the financial viability of the health care provider.

DC per patient calculates the average direct expenditure incurred by the hospital to provide a complete treatment cycle to a single patient. It includes the cost of specialized staff (physiotherapists) and the proportional cost of technology (robot depreciation and maintenance). It is an indicator of operational efficiency, showing how the robotic model can lower the "unit price of care" by scaling the number of patients treated.

Cost per FMA point gained is a cost-effectiveness indicator. It is calculated by dividing the DC per patient by the weighted average FMA improvement. It represents the financial investment required to achieve a single point of motor recovery on the FMA scale.

Staff engagement ratio (or supervision ratio) defines the relationship between the number of therapists and the number of patients treated simultaneously. In clinic B, this is a 1:1 ratio (1 therapist per patient), whereas in clinic A, it shifts toward a 1:2 or hybrid model. It quantifies workforce leverage, allowing therapists to oversee more treatments without increasing their physical workload.

Marginal clinical gain per patient represents the additional clinical improvement achieved by a patient in the robotic scenario (clinic A) compared with standard manual care (clinic B). It is calculated as the difference between the average FMA score improvement in the 2 scenarios. It quantifies the "added value" of technology in terms of individual recovery.

Clinical reach potential measures the department's ability to extend specialized rehabilitation to a broader portion of the target population. It is linked to increased patient throughput and reduced waiting lists. It quantifies the public health impact by measuring how many more patients can access high-quality treatment within the same time frame and infrastructure.

Scientific and Innovation Outcomes

Scientific and innovation outcomes were modeled as proxy indicators of research capacity rather than as direct outputs. These included the potential number of observational or pilot studies enabled by structured data collection, the volume of performance datasets generated annually, the estimated number of scientific publications and conference contributions, and the potential to initiate funded research projects and industrial collaborations. These outcomes were estimated based on the volume of treated patients and the availability of quantitative motor data produced by robotic systems.

Sensitivity Analysis

To assess the robustness of the model to assumptions, one-way and multiparameter sensitivity analyses were conducted on key variables, considering the economic and clinical outcomes. Two variables were chosen: patient volume and the robot use rate, which indicates the extent to which the robot unit is used and encompasses, in aggregate, the effects of the number of patients treated, the time the robot is not in use, and the number of patients handled by the therapists; and the cost per FMA point gained, as a measure of the effectiveness of the robot unit in improving the clinical quality of treatments. Threshold analyses were performed to identify minimum use rates and patient volumes required for economic sustainability.

Ethical and Regulatory Context

The present study was based entirely on a hypothetical simulation model and did not involve direct patient recruitment, interventions, access to individual clinical records, or the collection or analysis of identifiable or pseudonymized patient-level data. The model incorporated assumptions informed by current clinical practice and relevant regulatory frameworks for medical devices, including the European Medical Device Regulation (MDR 2017/745) [32] and internationally recognized technical standards issued by the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC), including ISO 13485 and the IEC 60601 series. Potential future clinical and kinematic data collection and secondary use were considered only as hypothetical scenarios, assuming appropriate anonymization and compliance with applicable data protection requirements, including the General Data Protection Regulation (GDPR) [33]. Any future observational studies conducted using the robotic unit would be subject to the applicable ethical review and regulatory requirements, including review by the relevant ethics committee where required, in accordance with the Declaration of Helsinki and applicable national regulations.

Results

Organizational Impact

The model suggests that clinic A achieved a higher annual patient throughput than clinic B (Table 2), with 960 vs 720 patients per year (+33%). This increase was associated with a higher total number of therapy sessions (12,480 vs 9360) and greater annual therapy hours (6240 vs 4680). The modeled transition from 720 to 960 annual patients reflects potential technical capacity rather than guaranteed market expansion. Actual patient volume intake is bounded by external constraints such as regional health care demand, referral networks, and institutional budgetary caps. When local demand limits volume growth, operational performance converges toward lower use bands, underscoring the importance of regional market alignment before capital adoption. Despite the higher activity volume, the required workforce was slightly lower in clinic A (2.34 vs 2.44 FTE), resulting in a substantial gain in productivity, expressed as sessions per FTE (+39%). Overall, the robotic-hybrid organizational model allowed higher service capacity with comparable or reduced staffing levels.

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Table 2 also shows that clinic A could manage a higher monthly patient volume than clinic B (80 vs 60 patients, +33%), corresponding to a higher number of therapy hours (520 vs 390 hours per month). Despite this increased workload, the estimated staff requirement was slightly lower in clinic A (2.34 vs 2.44 FTE). Consequently, staff efficiency, expressed as therapy hours per FTE, was markedly higher in the robotic-hybrid model (223 vs 160 hours/FTE and +63 hours/FTE), indicating a more efficient allocation of human resources.

The introduction of robotic units allows for a decoupling of patient throughput and staff requirements. While clinic B requires 2.44 FTEs to treat 60 patients, clinic A handles a 33% higher volume (80 patients) with a lower staff demand (2.34 FTEs), effectively increasing the therapy-to-staff productivity ratio by 39%.

Table 2. Organizational outcomes and staff requirements: comparison table.

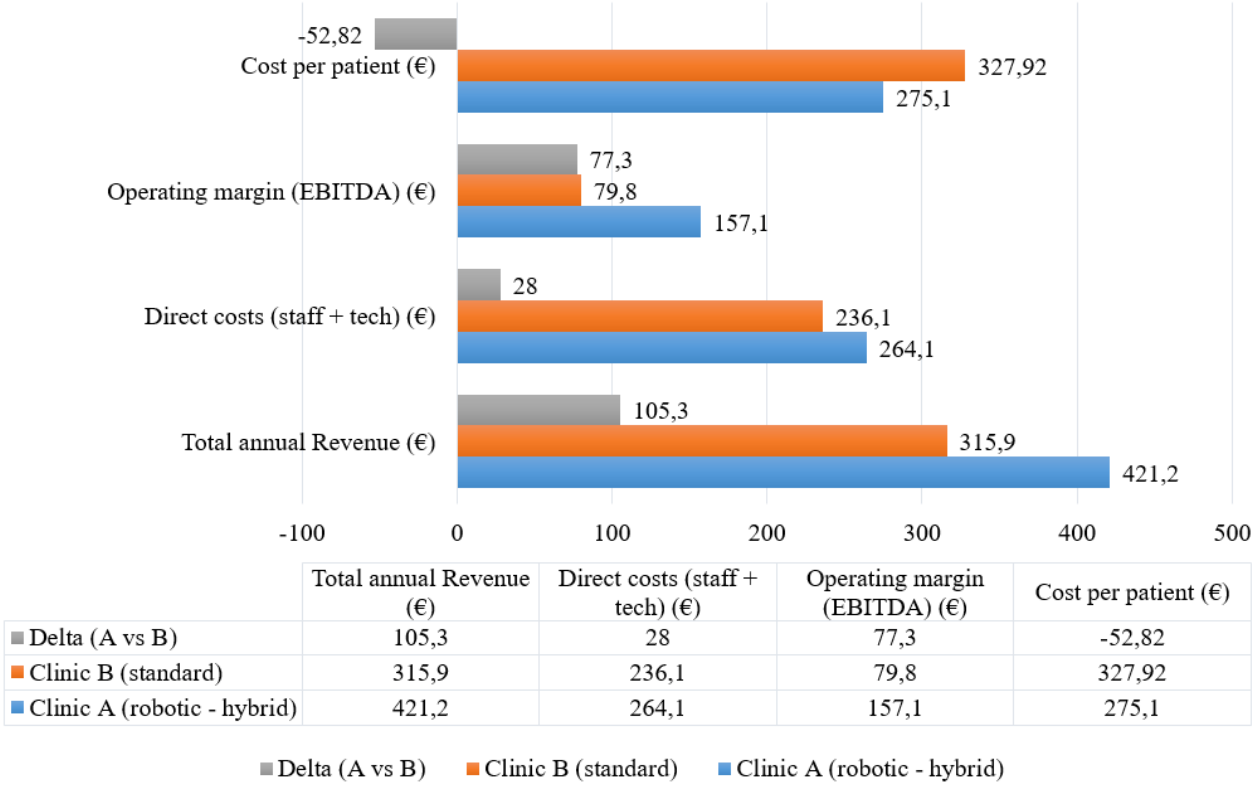
Parameter	Clinic A (robotic-hybrid model)	Clinic B (standard)	Difference (A vs B)
Patients per month, n	80	60	+20 (+33%)
Annual patient throughput, n	960	720	+240 (+33%)
Total annual sessions, n	12,480	9360	+3120
Annual therapy hours, n	6240	4680	+1560
Workforce needed, (FTE[a])	2.34	2.44	–0.10
Productivity (sessions/FTE)	5333	3836	+1497 (+39%)
Hours of therapy, n	520	390	+130 (+33%)
Efficiency (hours/FTE)	223	160	+63

[a]FTE: full-time equivalent.

Economic Impact

Under the assumptions, clinic A generated higher total annual revenue than clinic B (€421,200 vs €315,900), despite moderately higher DCs (€264,100 vs €236,100). This resulted in a substantially higher operating margin for clinic A (€157,100 vs €79,800). Furthermore, the robotic-hybrid model was associated with a lower cost per patient (€275.10 vs €327.92), corresponding to a reduction of €52.82 per treated patient (Figure 1).

Figure 1. Economic impact (per patient). Clinics A and B are compared with their difference. EBITDA: earnings before interest, taxes, depreciation, and amortization.



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Expected Clinical and Organizational Outcomes

Therapy Quality

Therapy quality is based on literature and not on model assumptions. Compared with standard therapy, robotic-assisted rehabilitation showed slightly higher performance across most therapy quality dimensions, particularly in repetition rate, protocol reproducibility, and availability of objective feedback (Table 3). The 2 approaches were assumed to have comparable intrinsic effectiveness when therapy dose is matched, in line with current meta-analyses. The observed quality advantage of scenario A was therefore mainly attributable to the capacity to deliver more intensive and standardized training rather than to a distinct clinical mechanism.

When normalized by functional gains, robotic-assisted rehabilitation showed comparable or slightly lower cost per unit of improvement than standard therapy. This effect was primarily driven by a higher therapy dose (greater repetitions and session frequency), which translated into moderately higher average motor and ADL improvements reported in the literature [8,11]. These results suggest that robotic rehabilitation is not intrinsically more effective but may achieve similar or better cost-effectiveness by enabling higher intensity of practice without proportional increases in staffing costs.

Table 3. Comparative therapy quality indicators based on literature.

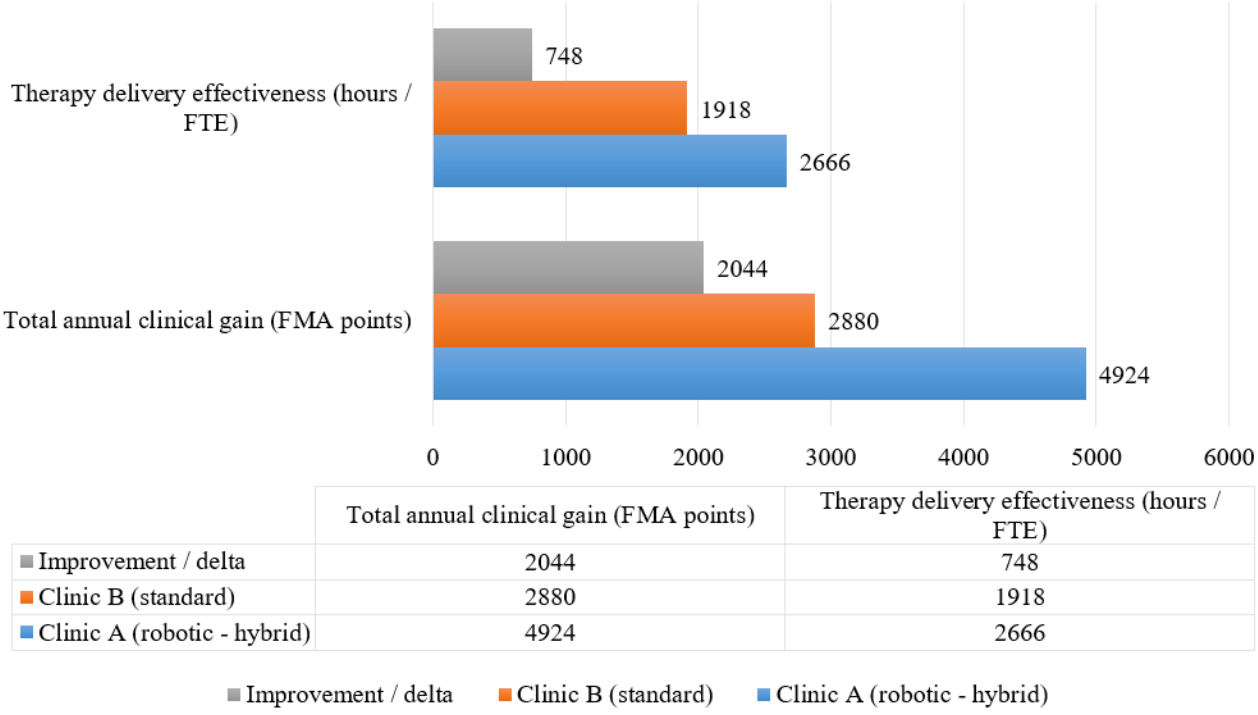
Dimension of therapy quality	Robotic-assisted rehabilitation	Standard rehabilitation	Evidence from literature
Repetitions per session	High (hundreds to >1000 movements per session)	Low to moderate (10 to approximately 100 repetitions per session)	Robotic devices enable massed practice and repetitive training [8,10,14]
Intensity control	Precisely programmable and reproducible	Therapist-dependent and variable	Robots allow controlled speed, force, and task difficulty [5,15]
Task specificity	High (goal-directed, trajectory-based, and task-oriented modes)	Variable (depends on therapist skill and fatigue)	Task-oriented robotic protocols support motor learning [4,14]
Intersession reproducibility	High (same protocol can be repeated identically)	Low to moderate (manual guidance variability)	Robotic training reduces intertherapist variability [15,17]
Objective performance feedback	Continuous (kinematics, forces, and errors)	Mainly qualitative and score-based	Robots provide high-frequency quantitative data [8]
Therapist physical workload	Reduced manual assistance	High physical effort for guidance and support	Robotic assistance reduces physical strain [14,17]
Access for patients with severe impairments	Higher (assistance-as-needed modes)	Limited by therapist burden	Robots allow early/intensive training in severe impairment [8,11]
Intrinsic therapeutic effectiveness	Comparable when dose is matched	Comparable when dose is matched	Still a matter of debate. No clear superiority when intensity is controlled [5,8]

Clinical Results (Economically Weighted)

The model suggests that clinic A has higher clinical performance than clinic B (Figure 2), with a higher weighted average improvement in FMA scores (5.13 vs 4.00 FMA points, +28.2%). This translated into a substantially greater total annual clinical gain (4924 vs 2880 FMA points, +71%), supported by higher therapy delivery effectiveness per FTE (+39%).

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Figure 2. Quantitative comparative rehabilitation effectiveness and cost-related indicators. FMA: Fugl-Meyer Assessment; FTE: full-time equivalent.



	Total annual clinical gain (FMA points)	Therapy delivery effectiveness (hours / FTE)
Improvement / delta	2044	748
Clinic B (standard)	2880	1918
Clinic A (robotic - hybrid)	4924	2666

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From an economic perspective (Table 4), clinic A was associated with lower DC per patient (−16.1%) and a markedly reduced cost per FMA point gained (€53.62 vs €81.98, −34.6%). In addition, the staff engagement ratio was lower in the robotic-hybrid model, indicating reduced relative personnel effort per unit of clinical output. Impact metrics further showed a marginal clinical gain per patient and an increased clinical reach potential (+240 patients per year, +33%), suggesting both clinical efficacy and expanded service capacity.

Table 4. Economic perspective.

Indicator	Clinic A (robotic-hybrid model)	Clinic B (standard)	Improvement/difference
Economic efficiency			
Direct cost per patient (€)[a]	275.10	327.92	–16.1%
Cost per FMA[b] point gained (€ per point)	53.62	81.98	–34.6%
Staff engagement ratio	0.72	1.00	–28% effort
Impact metrics			
Marginal clinical gain per patient (points)	+1.13	Baseline	Clinical advantage
Clinical reach potential (patients per year), n	+240	Baseline	+33% coverage

[a]€1=US $1.12 as of October 26, 2026.

[b]FMA: Fugl-Meyer Assessment.

Scientific and Innovation Perspectives (Qualitative Benefits)

While the simulation model focuses primarily on economic and organizational performance, the introduction of a robotic rehabilitation unit also creates qualitative opportunities for research and institutional development. Rather than acting as guaranteed measurable outputs, these dimensions represent potential structural benefits. The systematic logging of high-resolution kinematic and kinetic data provides a robust digital foundation for future observational studies and secondary data analyses, replacing sporadic traditional clinical scales with continuous multimodal datasets. Although absolute metrics such as publication counts or grant acquisitions cannot be reliably modeled, the presence of standardized technological infrastructure inherently enhances the facility's profile, facilitating academic networking, multicenter research alignment, and collaborative clinical innovation.

Sensitivity Analysis

Overview

To evaluate the robustness of the economic and organizational model, we performed a one-way sensitivity analysis on 2 critical parameters: robot use rate (reflecting clinical adherence) and

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total patient throughput (reflecting the hospital's ability to attract volume), reported in Table 5. The baseline values for clinic A (45 robotic patients per month, 80 total patients per month) were tested against "low use" and "volume stagnation" scenarios to identify sustainability thresholds.

Table 5. Sensitivity analysis: economic and organizational thresholds.

Parameter scenario	Scenario A	Total patients, n	Workforce (FTE[a])	Cost per patient (€)[b]	Difference vs standard care (clinic B)
Clinic B (reference)	0	60	2.44	327.91	—[c]
A1. Low use	25	80	2.73	310.50	–5.3% (marginal saving)
A2. Baseline (optimal)	45	80	2.34	275.10	–16.1% (significant saving)
A3. Volume stagnation	45	60	2.14	365.40	+11.4% (cost increase)

[a]FTE: full-time equivalent.

[b]€1=US $1.12 as of October 26, 2026.

[c]Not applicable.

Impact of Robot Use Rate (Clinical Adherence)

We simulated a scenario in which the robotic unit is underused due to lower clinical adoption or technical constraints, serving only 25 patients per month (approximately 30% of total throughput) instead of the baseline 45. In this "low use" scenario, the organizational efficiency of scenario A decreases significantly. To manage the remaining 55 patients via standard manual therapy (1:1 ratio), the workforce requirement increases from 2.34 FTEs (baseline) to 2.73 FTEs. Consequently, the net cost per patient rises to €310.50. This indicates that the economic advantage of the robotic unit is strictly dependent on maximizing its use; if use drops below a critical threshold of 30 patients per month (approximately 60% of capacity), the efficiency gains in workforce productivity are insufficient to offset capital depreciation.

Impact of Patient Volume (Scalability)

We assessed the financial risk associated with a failure to increase patient volume. In the "stagnation" scenario, clinic A invests in robotics but fails to attract external patients, maintaining the same throughput as clinic B (60 patients per month). Under these conditions, the fixed costs of the technology weigh heavily on a smaller patient base. The cost per patient in clinic A rises to €365.40, which is 11% higher than the standard care cost in clinic B (€327.91). This confirms that robotic rehabilitation acts as a "scale-enabler": it becomes economically sustainable only if the facility leverages the technology to increase total throughput above a break-even volume of approximately 70 patients per month.

Sensitivity Thresholds

The analysis identifies 2 necessary conditions for the economic viability of the robotic unit. The operational threshold requires the device to be used at least 60% of its theoretical capacity to generate sufficient FTE savings. The volume threshold requires the introduction of the technology to be accompanied by a minimum 15% to 20% increase in total patient volume to amortize fixed capital costs effectively. Failure to meet either condition results in a scenario in which robotic rehabilitation becomes a net cost driver rather than an efficiency multiplier.

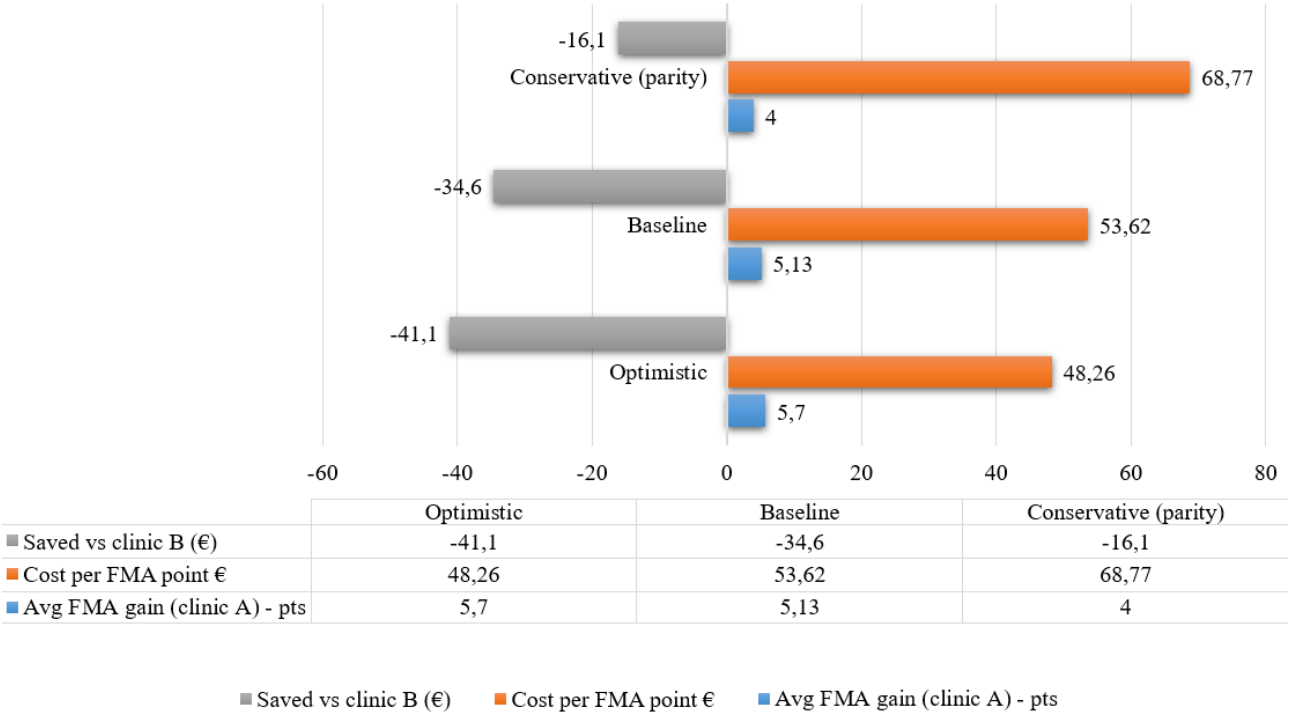
Sensitivity Analysis of Cost-Effectiveness: Cost Per FMA Point Gained

Sensitivity analysis was also conducted on the cost per FMA point gained, the primary indicator of value-based efficiency. The robustness of this metric was assessed by varying the clinical efficacy differential, defined as the additional FMA points gained through robotic therapy compared with standard care. In the baseline scenario, the robotic-hybrid model (clinic A) achieved an average improvement of 5.13 FMA points, compared with 4.00 points in clinic B, resulting in a 34.6% reduction in cost per point (€53.62 vs €81.98). Two alternative clinical outcomes were simulated. In the conservative scenario (clinical parity), both clinics achieved exactly 4.00 points, indicating that robotic therapy provided no additional clinical recovery over manual therapy. In the optimistic scenario (high intensity), the robotic group reached the upper bound of the expected improvement (7.0 points), increasing the weighted average improvement for clinic A to 5.70 points.

Assuming a fixed cost per patient of €275.10 (scenario A2 of the sensitivity analysis), even in the conservative scenario, where the robotic unit provides zero additional clinical benefit over manual therapy (clinical parity), clinic A remains 16.1% more cost-effective than clinic B (€68.77 vs €81.98). This suggests that the sustainability of robotic rehabilitation is "double-protected." The financial viability is guaranteed by the organizational efficiency (FTE optimization and higher throughput), even if the clinical superiority were to be marginal. Conversely, when clinical superiority is realized (baseline and optimistic scenarios), the cost-effectiveness scales exponentially, offering a massive advantage for health care providers focused on maximizing patient recovery within fixed budgets. Results are summarized in Figure 3.

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Figure 3. Sensitivity analysis of cost per Fugl-Meyer Assessment (FMA) point gained. Avg: average; pts: points.



	Optimistic	Baseline	Conservative (parity)
Saved vs clinic B (€)	-41,1	-34,6	-16,1
Cost per FMA point €	48,26	53,62	68,77
Avg FMA gain (clinic A) - pts	5,7	5,13	4

Discussion

The Robotic Workforce Multiplier

The results of this scenario-based simulation suggest that the introduction of a robotic rehabilitation unit in a medium-sized hospital (clinic A) may contribute to improving the "production function" of rehabilitative care. Unlike the traditional manual model (clinic B), which relies on a rigid 1:1 therapist-to-patient ratio, the hybrid model in clinic A may enable a decoupling of patient throughput from human workload. By optimizing the robotic units to a saturation point of 45 patients per month (representing approximately 56% of the total monthly caseload of 80 patients), clinic A may achieve a 33% increase in total volume compared with clinic B. Crucially, this expansion could be achieved without additional staffing. In fact, our FTE-based analysis reveals that clinic A requires only 2.34 FTEs to manage 80 patients, whereas clinic B requires 2.44 FTEs for just 60 patients. This efficiency gain is not attributed to an inherent clinical superiority of the robot in terms of recovery mechanisms but rather to its role as a workforce multiplier. In clinic A, the productivity ratio reaches 2666 therapy hours per FTE annually, a 39% improvement over the 1918 hours per FTE in clinic B. This allows the facility to absorb previously unmet rehabilitation demand while reducing the net cost per patient from €328 to €275.

Clinical Efficiency

The integrated analysis of clinic A's hybrid model reveals the possibility of a dual advantage over traditional care. First, the introduction of robotic units may enhance the quality of clinical outcomes. By enabling higher dosage, precision, and repeatability, the robotic treatment could lead to a weighted average FMA improvement of 5.13 points, compared with 4.00 points in the manual-only setting of clinic B (+28.2%). When scaled to the annual hospital volume, the impact could be substantial: clinic A produces a total annual clinical gain of 4924 FMA points, which is 71% higher than the 2880 points generated by clinic B. This metric suggests that a robotic-equipped facility acts as a far more powerful "health generator" for the community, potentially providing not just more care, but more effective recovery per patient.

The "Cost Per FMA Point" Paradigm

One of the most compelling findings of this study is the hypothetical possibility of a reduction in the cost of clinical recovery. In clinic B, the lack of technological support results in a high human-labor cost per unit of recovery, with each FMA point gained costing the facility €81.98. Conversely, in clinic A, the combination of a lower net cost per patient (€275.10) and clinical outcomes leads to a cost of €53.62 per FMA point. This 34.6% reduction in the cost of recovery represents a fundamental shift in hospital management. It demonstrates that the initial capital investment in robotics is not merely a "tech-upgrade" but a strategic move toward value-based health care. By lowering the cost of "producing" recovery, the hospital can reinvest the saved resources (approximately €28 per FMA point) into further expanding services or research.

Organizational Synergy and Workforce Productivity

The hybrid configuration of clinic A—where 45 patients use robotic units while 35 remain in standard care—is potentially a compelling organizational model. This setup allows the facility to handle a 33% higher patient volume with a theoretical workforce requirement of 2.34 FTEs, compared with the 2.44 FTEs needed for a lower volume in clinic B. The resulting staff engagement ratio of 0.72 in clinic A (ie, only 0.72 therapist-hours are required to produce 1 hour of therapy)

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highlights how technology mitigates the physical and temporal constraints of manual therapy. This "liberated time" is what enables the therapist to focus on high-level clinical decision-making and supervision, effectively increasing the therapy delivery effectiveness by 39% (2666 vs 1918 hours per FTE).

Organizational Implications: Scalability and Standardization

From an organizational perspective, the transition to an FTE-based resource management model highlights that technological investment is amortized through increased service capacity rather than staff reduction. The ability of a single therapist to supervise two robotic sessions simultaneously (1:2 ratio) effectively frees nearly 1 full therapist equivalent (0.91 FTE) compared with purely manual 1:1 delivery for the same volume. Furthermore, the robotic system introduces a level of operational standardization that is unattainable in manual therapy. Every session in clinic A follows precise, programmable protocols, reducing intertherapist variability and ensuring that patients with severe impairments receive a consistent, high-intensity dose of therapy (hundreds to thousands of repetitions per session) without increasing therapist physical fatigue.

Research and Innovation: Digital Transformation of Rehabilitation

Beyond economic and clinical metrics, the adoption of robotic technology offers qualitative advantages regarding data collection and research infrastructure. While our model does not formally quantify research output, the generation of continuous digital datasets ensures comprehensive traceability of training sessions. This technological environment serves as a qualitative enabler for observational research, supporting internal data consistency and fostering potential academic and industrial partnerships. Rather than positioning the clinical unit as an immediate quantitative "innovation hub," these capabilities should be viewed as long-term institutional opportunities that depend heavily on internal research governance and strategic academic engagement. The projected benefits in terms of clinical gains (FMA improvements) and cost efficiencies are heavily contingent upon institutional adoption rates, consistent device use, and local reimbursement structures. Future empirical implementations are necessary to validate these theoretical projections against real-world clinical variabilities.

Limitations

Despite the promising insights provided by this comparative analysis, some limitations should be acknowledged. First, this study relies on a scenario-based simulation model rather than longitudinal empirical data. While the model parameters—such as patient throughput, device costs, and staffing ratios—were derived from established clinical literature and realistic hospital benchmarks, they may not be applicable to every institutional setting. In fact, while these parameters were derived from robust clinical benchmarks and manufacturer specifications, the absence of real-world calibration means that the projected outcomes reflect idealized operational assumptions. Consequently, the quantitative outputs—such as exact cost reductions and throughput margins—should not be interpreted as absolute predictions but rather as comparative estimates illustrating structural organizational dynamics. Future research will prioritize multicenter prospective validation studies to calibrate these simulation parameters against longitudinal, real-world clinical and financial workflows.

We acknowledge that factors such as specific regional reimbursement policies, variations in labor costs, and the architectural constraints of different hospitals could influence the analysis. The clinical outcomes modeled in this study, specifically the weighted average FMA improvement, were estimated based on aggregated data from meta-analyses. While these values provide a robust baseline, they do not account for the high variability in individual patient recovery trajectories, which are influenced by the timing of intervention, lesion severity, and comorbidities. Third, the organizational "multiplier effect" assumes a consistent 1:2 therapist-to-patient ratio during robotic sessions. In practice, the initial learning curve for clinical staff and potential technical downtime may temporarily reduce this efficiency during the first year of implementation. Finally, the scientific and innovation outcomes are presented as proxy indicators of research potential. While the capacity for data generation is a clear technical advantage of robotic units, the transformation of these datasets into high-impact publications depends on the hospital's internal research infrastructure and academic partnerships, which were not modeled. Other factors, such as real-world operational complexities—including patient transfer delays, device donning and doffing procedures, hygiene and disinfection protocols, unexpected technical downtime, spatial limitations, and long-term mechanical wear and tear—were not modeled at a microanalytical level. While annualized maintenance costs partially offset hardware degradation, high-frequency operational frictions can temporarily reduce the effective daily use rate. Consequently, actual hospital implementations must account for these microenvironmental overheads when targeting the operational efficiency thresholds identified in our sensitivity analysis. Moreover, the baseline assumption of a 100% robot use rate represents a theoretical operational ceiling rather than a realistic daily average. In actual clinical practice, auxiliary activities such as patient positioning, device donning and doffing, and routine software calibration consume a portion of the operational window. Nevertheless, our sensitivity analysis explicitly models underuse thresholds (eg, lower operational saturation), demonstrating that while efficiency margins compress, the model retains economic viability provided that use remains above the critical break-even limit. The analysis was conducted strictly from the institutional hospital perspective, omitting a patient-level microsimulation or a broader societal perspective. While institutional decision-making is primarily governed by operational budgets, throughput capacities, and direct labor costs, future investigations should incorporate patient-level longitudinal tracking to capture individual variability in recovery trajectories and out-of-pocket expenses. Finally, while conventional therapy is subject to performance variability driven by physical therapist fatigue, robotic pathways rely on electromechanical consistency. Nonetheless, operational continuity in robotic settings can occasionally be modulated by technical factors such as routine software recalibrations or minor

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maintenance interventions, elements that are mitigated by standardized service agreements and safety protocols. Future research should focus on multicenter prospective studies to validate these simulation-based findings with real-world longitudinal evidence. Results may not generalize to hospitals with different reimbursement schemes or staffing costs.

Addressing Secondary Economic Variables and Operational Downtime

Although the current sensitivity analysis focused on primary throughput and cost boundaries, we acknowledge that secondary operational factors—such as unexpected robotic downtime, fluctuations in specialized physiotherapist wages, regional variations in reimbursement tariffs, and escalating maintenance agreements—represent real-world variables that could influence economic margins. In practice, a severe increase in technical downtime (reducing device use below critical operational thresholds) or a downward revision of regional Diagnosis-Related Group tariffs would compress the gross operating margin (EBITDA) calculated in clinic A. Nevertheless, the structural robustness demonstrated across our high- and low-use sensitivity ranges suggests that the model maintains economic viability provided that patient volume remains stable. Future implementations should incorporate real-world stochastic tracking of these secondary parameters as longitudinal data become available.

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Generative AI Use

The authors declare the use of generative AI (GenAI) in the research and writing process. According to the GAIDeT (Generative AI Declaration Taxonomy; 2025), the following tasks were delegated to GenAI tools under full human supervision: reproducibility testing, proofreading and editing, translation, quality assessment, and identification of limitations. The GenAI tool used was Gemini 1.5 (Google). Responsibility for the final manuscript lies entirely with the authors. GenAI tools are not listed as authors and do not bear responsibility for the final outcomes.

Authors' Contributions

AS conceived the paper, analyzed the data, wrote the paper, provided funding, and administered the project.

Conflicts of Interest

None declared.

Multimedia Appendix 1

CHEERS checklist.
[DOCX File , 20 KB-Multimedia Appendix 1]

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Abbreviations

ADL: activities of daily life
CHEERS: Consolidated Health Economic Evaluation Reporting Standards
DC: direct cost
EBITDA: earnings before interest, taxes, depreciation, and amortization
FMA: Fugl-Meyer Assessment
FTE: full-time equivalent
GDPR: General Data Protection Regulation
IEC: International Electrotechnical Commission
ISO: International Organization for Standardization
MDR: Medical Device Regulation

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