scientific reports

OPEN

The socio-economic impact of robotic prosthetics: the Hannes hand case study

Sara Preti[1]✉, Giulia Caserta[2], Lorenzo De Michieli[2,4], Nicolò Boccardo[2,3] & Enrico di Bella[1]

Social impact assessment has gained increasing attention in recent years, emphasizing the added value and social changes brought by project activities alongside the sustainability of social actions. This study evaluates the economic and social impact of a robotics research project culminating in the development of Hannes, an advanced prosthetic hand resulting from collaboration between the Italian Institute of Technology and the Italian National Insurance Institute. Hannes is used in robotic assistance to treat individuals with upper limb differences. Data were collected through a clinical study involving myoelectric prostheses users who underwent functional and psychosocial assessments before and after using Hannes. The Social Return On Investment (SROI) methodology is employed to evaluate the impacts of the robotic device by analyzing qualitative, quantitative, and financial data to estimate the value created by research activities. Preliminary results suggest that for every euro invested, approximately 9 euros of social value are generated. This revelation highlights the substantial positive impact of Hannes and underscores the potential for further advancements in the field of robotics to improve the lives of individuals with limb loss. By providing a comprehensive analysis, this research contributes to understanding the broader social benefits of innovative healthcare technologies that mitigate social inequalities.

Keywords Social impact assessment, SROI, Robotics, Limb difference, Hand prosthesis

In today's rapidly evolving healthcare landscape, technological advancements not only improve patient outcomes but also influence the framework of health policy. One notable innovation is the development of advanced prosthetic devices, such as robotic prosthetic hands.

Hand loss profoundly alters the lives of people, affecting their economic stability and social well-being. Hands, with their numerous degrees of freedom (that is, the number of independent movements), play a crucial role in daily activities and interactions[1]. The ability to perform a wide range of movements, from powerful to precise tasks, makes the hand indispensable for independence in daily, social, and work activities. The impact of limb amputation extends beyond physical limitations, often leading to mental distress, depression, and altered perception of oneself and one's body[2]. The high incidence of these injuries[3], which cause significant physical, psychological, and social complications[4], further underscores the importance of advanced prosthetics in improving the quality of life for those affected. Moreover, such events have far-reaching implications, not only for the individual amputee, but also for their families and close social circles[5,6]. Additionally, amputations place significant demands on the healthcare system, highlighting the broader societal costs and consequences associated with such injuries[7].

The Italian National Institute of Health reports an average of approximately 2,734 upper limb amputations per year, of which about 106 cases specifically involve the hand[8].

The major cause of these upper extremity amputations is related to trauma[9], primarily due to industrial and road accidents, as well as other traumatic events[10].

The emergence of robotic hands represents a significant leap beyond traditional passive and body-powered prostheses. Electrically powered prosthetics have drastically improved the quality of life for people with limb loss, offering greater functionality and independence[1,11].

These devices use battery power to drive electric motors, converting electrical energy into mechanical motion for the prosthetic components. These prostheses are typically controlled by electromyographic signals from the residual muscles of the patient's limb. Myoelectric prostheses offer significant advantages, including high gripping

[1]Department of Political and International Sciences, University of Genoa, 16125 Genoa, Italy. [2]Rehab Technologies Lab, Istituto Italiano di Tecnologia, 16163 Genova, Italy. [3]Open University Affiliated Research Centre at Istituto Italiano di Tecnologia (ARC@IIT), Istituto Italiano di Tecnologia, 16163 Genova, Italy. [4]Technology Transfer Office, Istituto Italiano di Tecnologia, 16163 Genova, Italy. ✉email: sara.preti@edu.unige.it

strength and realistic aesthetics[12]. However, they also have limitations. Their electromechanical components make them heavier in comparison to either body-powered or passive devices[12], thus leading to increased muscle fatigue during extended use. In addition, patients need to undergo training with physiotherapists to fully utilize the functionalities of the prosthesis[1,13,14]. In addition, these are expensive due to their advanced technology, and may not be suitable if the patient's electromyographic signal is too weak[15,16].

While initially costly[17,18], they can reduce long-term healthcare expenses by minimising rehabilitation needs and psychological support costs. These cutting-edge technologies not only promise to improve individual rehabilitation outcomes but also contribute to the sustainability and efficiency of healthcare systems.

This study evaluates the economic and social impact of *Hannes*, an advanced myoelectrically controlled, poly-articulated robotic hand prosthesis that seeks to revolutionize the assistance for the treatment of individuals with limb loss. Hannes has been developed by the Rehab Technologies Lab, a joint laboratory established in December 2013 through a collaboration between the Italian National Insurance Institute (INAIL) and the Italian Institute of Technology (IIT) to create innovative high-tech, and cost-effective solutions for patients with disabilities. INAIL, Italy's public system of compensation for occupational diseases[19], has played a key role in developing innovative prosthetic solutions through its Centro Protesi in Vigorso di Budrio. To comprehensively assess the broader effects of the Hannes project, this study uses the Social Return On Investment (SROI) methodology. This framework captures both financial and social outcomes, highlighting how advanced prosthetic technologies can generate significant value for patients, healthcare systems, and society as a whole. This paper is structured to provide an overview of the research project and its context, a detailed explanation of the data and methodology used, and an analysis of the results of the case study with their broader implications.

Materials and methods

Hannes hand prosthesis

This study examines the socio-economic impact of Hannes, a robotic hand prosthesis developed by INAIL and IIT[20], shown in Fig. 1. Positioned within the rapidly growing field of rehabilitation robotics, this advanced technology contributes to a market projected to reach almost USD 500 million by 2025, with an anticipated compound annual growth rate of 15.2% from 2025 to 2030[21].

The project involved researchers, orthopedists, and industrial designers who collaborated with end-users to address their clinical and social needs. Hannes restores over 90% of the functionality of the upper limb[20], enabling users to regain the ability to perform activities of daily living (ADLs). Compared to commercial equivalent prostheses such as Ottobock's Michelangelo and Bebionic, and Ossur's i-Limb, widely considered the gold standards among hand prostheses, Hannes offers several advantages.

First, it automatically adapts to the shape of the grasped objects thanks to its embedded mechanical differential system, providing a stronger and more natural grip. The hand prosthesis allows passive thumb positioning for various grasp types (fine, lateral, power). Moreover, a passive wrist module enables pronation and supination, as well as flexion-extension, thus minimising compensatory movements. Overall, Hannes provides human-like grasping behavior, closely replicating the kinematics of a natural hand. Additionally, Hannes presents a longer-lasting battery, ensuring all-day use, and it is less expensive, with costs approximately 30% lower than competing devices.

Hannes incorporates a set of surface electromyographic (EMG) sensors applied inside the custom socket, which detect the activity in the residual forearm muscles. This enables intuitive control of the prosthetic hand: as the user actively contracts his muscles, the resulting signals are detected by the device and translated into precise, corresponding movements of the prosthesis[22]. A single motor powers the poly-articulated hand, with tendons coordinating the opening and closing of all fingers.

Another key feature of Hannes is its anthropomorphic design, including realistic size, weight, and appearance, which has also been recognized by the Compasso D'Oro ADI Prize in 2020. Specifically, the hand weighs 480

Fig. 1. Views of the Hannes hand without cosmetic glove.

grams and mimics the aesthetics of the natural hand. It is available in both left - and right versions, and it can be accompanied by a male or female cosmetic glove.

Users can adjust movement precision and speed through dedicated software that can be wirelessly customized via a Bluetooth interface. A short, one-week training with the physiotherapists allows the limb difference subject to proportionally and autonomously take full advantage of the Hannes' functionalities.

The combination of its anthropomorphism, biomimetic performance, and human-like grasping makes Hannes a high-quality prosthesis that meets all the essential criteria for excellence[20].

Data acquisition and experimental procedure

A clinical trial conducted by IIT and INAIL, described and analyzed in the present study, evaluated functionality, user experience (e.g., independence in performing ADL), and embodiment, the integration of the prosthesis into the user's body schema. The study involved 11 trans-radial amputees using myoelectric prostheses for more than a year, who were selected according to strict eligibility and inclusion criteria.

Inclusion criteria required participants to be adults between 18 and 65 years, have a transradial amputation, and have already used another myoelectric hand prosthesis for more than one year. Participants also had to provide their informed consent for both participation and data processing.

Exclusion criteria included refusal to provide informed consent; presence of comorbidities or concurrent disabilities that could interfere with the study; skin lesions on the residual limb affecting prosthesis use; presence of implanted cardiac medical devices (e.g., pacemakers or automatic implantable cardioverter-defibrillator); use of medications or substances that may interfere with sensory or motor functions; visual impairments; declared psychological or psychiatric conditions; inadequate level of cooperation; and pregnancy or breastfeeding. Other conditions that could compromise adherence to the study protocol were also grounds for exclusion.

Table 1 summarizes the demographics of the participants. Most participants were male, with an average age of 49 years. Nearly all had work-related amputations, an average of 29 years since amputation, and used their prostheses for more than 10 hours per day. All assessments took place at the INAIL Prosthetic Center in Budrio. Each participant provided written informed consent before the study, which followed the principles of the Declaration of Helsinki and received approval from the Ethics Committee of Area Vasta Emilia Centro (Protocol code: CP-PPRAS1/1-03).

Data were collected using internationally validated self-report questionnaires:

- The *NASA Task Load Index* (NASA-TLX) measures subjective workload and assesses the mental demands experienced by an individual during a task[23].
- The *System Usability Scale* (SUS) evaluates the user's perception of the prosthesis's usability and overall user experience[24,25].
- The *Trinity Amputation and Prosthesis Experience Scales-Revised* (TAPES-R) assesses patient satisfaction in using the prosthesis across various tasks[26].
- The *Orthotics and Prosthetics User Survey - Upper Extremity Functional Status* (OPUS-UEFS) module measures daily activities performed by amputees with the prosthesis, such as self-care and the use of household tools[27].
- The *Quick Disabilities of the Arm, Shoulder, and Hand* (QuickDASH) evaluates limitations in ADLs, work, sports, and symptoms in the upper limb[28].

Almost all questionnaires used Likert scales (typically rated from 1 to 3, 5, or 7 points) and were administered in Italian, the native language of the participants. Moreover, a custom questionnaire was designed to investigate user experience and embodiment. Functional performance was evaluated by using the *Minnesota Manual Dexterity Test - Placing* (MMDT-P)[29], the *Southampton Hand Assessment Procedure* (SHAP)[30], and the *Box and Blocks Test* (BBT)[31]. These tests assess and measure the functional capabilities of a prosthetic hand during tasks inspired by ADL. Finally, embodiment was assessed via the *Rubber Hand Illusion* (RHI)[32], proprioceptive tasks, postural equilibrium analysis, and the custom questionnaire to evaluate the prosthesis's integration into the

ID	Age (yr)	Sex	Amputation side	Dominant hand	Time since amputation (yr)	Employment	Sport recreation
1	42	F	L	R	18	Employee	Swimming and video games
2	53	M	R	R	31	Supermarket employee	Singing
3	58	M	R	R	36	Employee	Sitting volley and archery
4	54	M	R	R	22	Farm worker	Shooting range
5	59	M	R	R	46	Employee	Cycling and horse riding
6	59	M	R	L	57	Retired teacher	Trekking and gardening
7	33	M	R	R	22	Architect	Running
8	37	M	L	R	16	Video terminal employee	Horse riding, cycling, and gardening
9	31	M	R	R	7	Electrical panel designer	MTB
10	33	M	R	R	13	Employee	Gardening
11	65	M	R	R	54	Retired	Carpentry

Table 1. Characteristics of the sample of clinical trial participants.

user's body schema. A detailed description of the questionnaires and tests can be found in Appendix A of the online Supplementary material.

A literature review of similar studies was conducted to support the validity of the study design and to justify the chosen sample size. For example, D'Alonzo et al.[33] reported significant effects with only 9 participants with limb-difference, using a repeated-measures ANOVA in embodiment paradigms, indicating that large within-subject effects can be reliably detected even with small samples. Similarly, other studies evaluating upper-limb prostheses using the same self-report measures enrolled comparable or even smaller sample sizes[34,35]. Initially, we planned to include 13 patients in the clinical trial. However, due to delays caused by the COVID-19 pandemic, data were ultimately collected from 11 patients. Nevertheless, considering the repeated-measures design adopted in our protocol (which increases statistical power by reducing inter-subject variability) and the precedent set by previous studies, the current sample size can be considered adequate to detect meaningful effects and is in line with the methodological standards in this field.

The study timeline is shown in Fig. 2. At baseline time (TB), patients completed initial assessments using their myoelectric prostheses. Orthopedic technicians at the INAIL Prosthetic Center of Budrio then configured Hannes for each participant. At T0, pre-training functional tests were conducted using Hannes, followed by a four-day (4 hours/day) rehabilitation program focusing on general manipulations (hand opening/closing, object grasping) and ADLs (e.g., setting a table, cutting fruit, tying shoelaces). After training (T1), participants repeated the assessments. Subsequently, they used Hannes in daily life for three months, with evaluations at the end of each month (T2, T3, T4).

This study provides a preliminary assessment of the project's social impact, with a primary focus on patients as the main beneficiaries. Despite limitations due to available data, it also identifies other key stakeholders - including caregivers, orthopedists, orthopedic workshops, local health authorities (ASL), and INAIL - and offers an estimate of their potential outcomes and social impact.

Social return on investment (SROI): an overview

Social impact assessment evaluates, monitors, and manages the economic, social, and environmental effects of an organization's activities, both positive and negative, whether intended or not[36]. Various tools have been developed for this purpose, with contributions from academic institutions to international organizations, credit institutions, and individual entities or associations[37]. These tools include frameworks like those developed by the Global Reporting Initiative and the Global Impact Investing Network. However, many of these frameworks emphasize outputs over outcomes. Furthermore, some methodologies are designed for specific sectors, such as non-profits (e.g., Social Enterprise Impact Evaluation, European Venture Philanthropy Association). While others can be applied across various contexts, they may still overlook key stakeholders involved in the project, intervention, or activity. To overcome these limitations, we adopted the Social Return on Investment (SROI) methodology, originally developed by J. Emerson at Harvard Business School[38], and later refined in Europe by organizations such as the *New Economics Foundation* and *Social Value UK*. In Italy, the *Human Foundation* has been a key advocate. Today, SROI is one of the most recognized methods for social impact assessment[39–41].

SROI extends traditional ROI by incorporating social and environmental value. It follows the Impact Value Chain (IVC)[42] and integrates elements of Cost-Benefit Analysis (CBA)[43]. Unlike CBA, SROI adopts a participatory approach, emphasizing stakeholder engagement. Its flexibility makes it suitable for private, non-profit, and public sector evaluations.

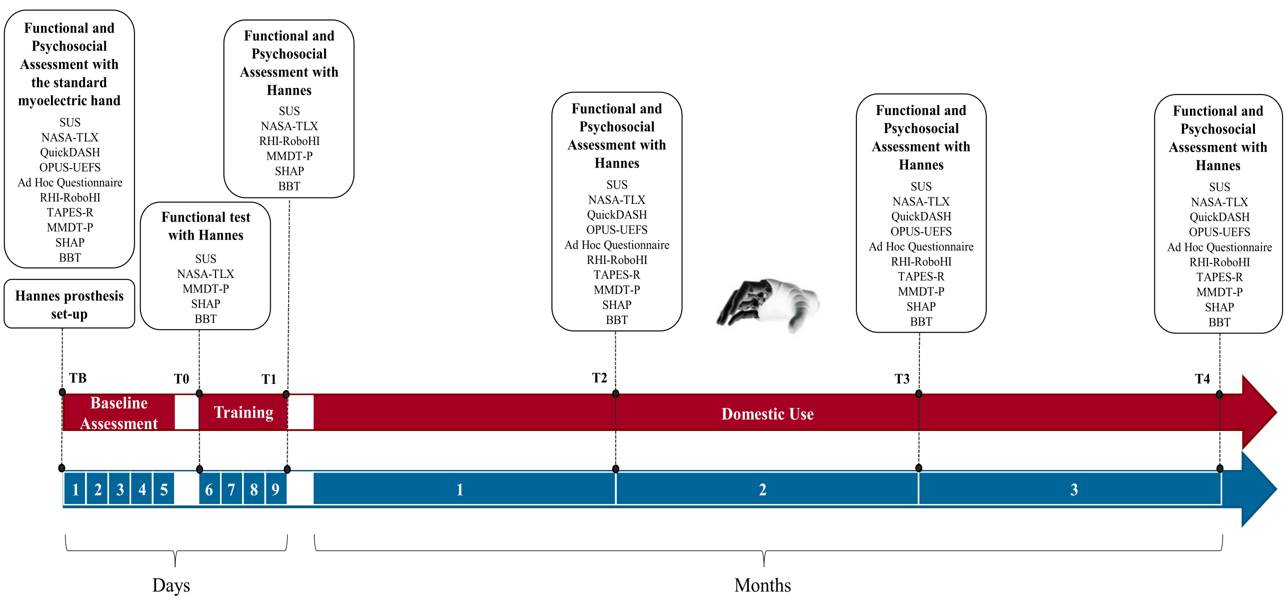

Fig. 2. Study design of the clinical trial.

SROI can be applied in forecasting (estimating future impact) or evaluative (assessing realized impact) analyses, both structured around six key stages:

1. Defining the Scope: This phase sets the objectives, stakeholders, available resources, and time frame, distinguishing between forecasting and evaluative SROI. Key stakeholders - those who experience or are affected by the intervention, either positively or negatively—are identified and engaged.
2. Mapping Outcomes: Using the IVC, inputs (resources) are linked to outputs (the immediate, tangible products of the activities) and outcomes (the resulting changes experienced by stakeholders). Stakeholders play a key role in defining and quantifying impacts.
3. Measuring Outcome and Assigning Monetary Value:

- Outcome indicators are selected, and data are gathered from primary sources (interviews, focus groups, surveys) or secondary sources (archival records, research).
- The duration of outcomes is considered, accounting for effects persisting beyond the intervention.
- Monetary values are assigned to each outcome. Financial proxies estimate the social value of non-market assets. Some monetization processes are straightforward, such as cost savings or income generation. Others require more complex estimation techniques, including stated preference surveys, where beneficiaries estimate the value of an asset, and other techniques such as hedonic pricing and travel cost methods.

4. Calculating impact: To ensure accuracy and prevent overestimation of impacts, the following adjustments may be applied:

- Deadweight (the portion of impact that would have occurred regardless of the intervention)
- Attribution (the share of impact attributable to external factors)
- Displacement (whether benefits come at the expense of another stakeholder)
- Drop-off (the reduction in impact over time, beyond one year)

The Present Value of each outcome (PV_j) is computed by multiplying the financial proxy by the outcome quantity and adjusting for deadweight, attribution, displacement, and drop-off. As shown in Equation 1, PV_j is determined by discounting future benefits using a discount factor calculated from an appropriate interest rate (e.g., UK HM Treasury's 3.5% standard rate). This reflects the time value of money and converts future impacts into their present value.

$$PV_j = \sum_{t=1}^{n} (Proxy_j \cdot Outcome_j)\,(1 - DW_j)(1 - ATTR_j)(1 - DISP_j)(1 - DO_j)\frac{1}{(1+r)^t} \quad (1)$$

where *DW* = deadweight, *ATTR* = attribution, *DISP* = displacement, *DO* = drop-off, *n* = number of years, and *r* = discount rate.

5. Computing the SROI Ratio: The SROI ratio expresses the social value generated per unit of investment (e.g., a ratio of 4 means that every €1 invested yields €4 of social value).
6. Reporting and Stakeholder Communication: Findings are shared transparently, adhering to SROI principles outlined in the SROI Network's guide[44]. This step also verifies that organizations do not claim value beyond their actual contribution.

From these six stages, SROI can be defined as a mixed-methodology approach, integrating qualitative stakeholder insights with quantitative economic valuation to provide a comprehensive social impact assessment.

The strengths of SROI include its ability to synthesize complex data into a single monetary value, improving communication. It supports efficient resource allocation and enhances stakeholder engagement. Additionally, it strengthens accountability and credibility among funders, financial institutions, and policymakers while aligning with New Public Management reforms, which emphasize efficiency and outcome measurement.

However, SROI has limitations. Only some intangible assets can be quantified using concrete indicators, while others, like well-being or self-esteem, rely on subjective measures. King[45] highlights additional challenges such as high costs, time demands, and data constraints. King also notes the difficulties in involving all stakeholders in the evaluation process and the presence of subjectivity in selecting measurement criteria.

Additionally, attributing outcomes, determining discount rates, and setting time horizons increase complexity. While SROI allows internal comparisons over time, cross-entity comparisons remain difficult due to variations in stakeholders and methodologies.

Item-scale correlation and Cronbach's alpha

As described in the previous paragraph, according to SROI theory, once the outcomes have been mapped, the next step is to measure them using appropriate indicators. Most indicators were derived from specific items within the questionnaires administered to participants during the clinical trial. Each outcome could be measured by a single indicator or by a set of multiple indicators.

In case of multiple indicators, a normalization was applied using the min-max method since items are often measured on different scales. This transformation rescaled all indicator values to a common range between 0 and 1, enabling comparability across measures. Furthermore, all indicators were adjusted to have positive polarity[46] to ensure that higher indicator values consistently represent more favorable outcomes.

When multiple indicators were used to measure a single outcome, it was essential to verify that all selected items aligned with the intended construct. To this end, we employed statistical methods that are particularly suitable for Likert and other rating scales. One such method is the *item-scale correlation*, a correlation coefficient that measures the relationship between the scores of individual items and the aggregate score of the scale. A high positive correlation indicates that the item is strongly aligned with the underlying construct. In contrast, a low or negative correlation indicates that the item may not effectively capture the intended concept. Item-scale correlation is particularly valuable for identifying items that deviate from the global score across a significant number of respondents. Such discrepancies may result from ambiguous wording, leading to respondent misunderstandings, or from items unintentionally measuring a concept different from the one intended. In either case, items that did not align well with the rest of the scale were removed to maintain consistency.

Cronbach's alpha[47] was also applied to assess internal consistency among selected items. It is computed based on the correlation matrix between all items and their total number, as shown in the following equation:

$$\alpha = \frac{n\overline{r}}{1+\overline{r}(n-1)} \tag{2}$$

where n is the number of items, and $\overline{r}$ is their average correlation. Although Cronbach's alpha resembles a correlation coefficient, it is not a direct correlation measure. It ranges from 0 to 1, with higher values indicating greater internal consistency. According to Nunnally's guideline (1978)[48], a value above 0.70 generally suggests satisfactory reliability. Items with low item-scale correlations were systematically removed to enhance alpha, balancing the trade-off between the number of items (n) and their average correlation ($\overline{r}$). This process refined the scale's reliability, as shown in Table 2, where iterative eliminations improved alpha. Table 2 outlines an item-level analysis for the job reintegration outcome, including Cronbach's alpha (α), item-scale correlations (r), and the alpha value if each item is removed. Initially, the scale exhibited satisfactory internal consistency ($\alpha = 0.812$). However, variability in item correlations was observed. The lowest correlation ($r = 0.165$) was found for item quickDASH_12. Removing this item increased α from 0.812 to 0.843, justifying its exclusion. The process was iterated until all remaining items showed high correlations and no further removal improved α.

This approach was applied to all outcomes defined by multiple elementary indicators.

Results

This study assesses the socio-economic impact of Hannes using the SROI framework, which quantifies the benefits generated for a wide range of stakeholders. These include, first and foremost, patients, as well as caregivers, orthopedists, orthopedic workshops, local health authorities (ASL), and institutions such as INAIL. By analyzing the outcomes and changes associated with the use of the Hannes device, the study evaluates both tangible and intangible benefits, such as improved quality of life for patients and reduced healthcare costs, providing an estimate of the broader social value generated for each stakeholder group.

Table 3 offers a comprehensive overview of each stakeholder, detailing their specific outcomes. It also identifies the most suitable indicators for impact evaluation, their quantification, and the estimated economic value or financial proxies used to monetize both tangible and intangible outcomes. The total monetary impact incorporates deadweight percentages, which measure changes that would have occurred without the Hannes device. In this study, deadweight percentages were calculated using the questionnaires referenced in the previous paragraph to identify patients who would have achieved similar outcomes with their regular prostheses.

The study identified nine outcomes: six for patients (primary beneficiaries), one for caregivers, and two for broader stakeholders, including healthcare professionals and supporting institutions.

Item id	Description	Step 1		Step 2		Step 3		Step 4		Step 5	
		r	α if the item is removed	*r*	α if the item is removed	*r*	α if the item is removed	*r*	α if the item is removed	*r*	α if the item is removed
quickDASH_12	Did you have any difficulty doing your work in your usual way?	0.165	0.843	–	–	–	–	–	–	–	–
quickDASH_08	During the past week, were you limited in your work or other regular daily activities as a result of your arm, shoulder or hand problem?	0.324	0.819	0.356	0.854	–	–	–	–	–	–
quickDASH_13	Did you have any difficulty doing your usual work because of arm, shoulder or hand pain?	0.426	0.796	0.476	0.825	0.418	0.862	–	–	–	–
TAPES-R_11	An artificial limb interferes with the ability to do my work	0.478	0.802	0.482	0.844	0.505	0.857	0.545	0.864	–	–
TAPES-R_13	Having an artificial limb limits the kind of work that I can do	0.568	0.782	0.544	0.828	0.55	0.842	0.55	0.854	0.647	0.847
quickDASH_15	Did you have any difficulty spending your usual amount of time doing your work?	0.612	0.781	0.572	0.833	0.62	0.83	0.603	0.845	0.705	0.830
TAPES-R_15	Having an artificial limb limits the amount of work that I can do	0.874	0.738	0.881	0.778	0.848	0.793	0.827	0.797	0.706	0.836
quickDASH_14	Did you have any difficulty doing your work as well as you would like?	0.881	0.739	0.894	0.777	0.885	0.784	0.842	0.797	0.818	0.793
		$\alpha = 0.812$		$\alpha = 0.843$		$\alpha = 0.854$		$\alpha = 0.862$		$\alpha = 0.864$	

Table 2. Cronbach's alpha computed for the list of indicators relating to job reintegration outcome.

Stakeholder	Outcome	Indicator	Quantity	Valuation approach and source	Monetary valuation	Deadweight	Impact calculation
Patients	Restore over 80% of functionality of a real hand	Synthetic Index IoF (SHAP)	5	Prudential estimate of the compensation paid by INAIL to the worker for the loss ofpsychophysical integrity following a workplace accident Source: INAIL	34,238.44	0%	171,192.20
	Possibility of performing ADLs and improved functional independence	All indicators selected using Cronbach's alpha	8	Estimated annual cost of a caregiver (based on the minimum hourly wage in Italy) Source: ISTAT	10,800.00	50%	43,200.00
	Job reintegration	All indicators selected using Cronbach's alpha	10	Monthly allowance for disabled persons who are recognized as having a partial reduction in their capacity to work and whose annual income is below the thresholds provided for by law Source: INPS	4081.61	90%	4081.61
	Social reintegration and reduction of social isolation	All indicators selected using Cronbach's alpha	8	Annual membership fee for team sports Source: ISTAT	683.71	38%	3418.55
	Embodiment	Indicator ADHOC_15	8	Prosthesis abandonment rate for expenditure incurred by INAIL for its replacement Source: IIT	3309.16	88%	3309.16
	Increased self-esteem	All indicators selected using Cronbach's alpha	10	Avg cost of improving confidence and self-esteem (10 counseling meetings) Source: Tariffario nazionale psicologi e psicoterapeuti	750.00	50%	3750.00
Caregivers	Reducing caregiver burden	All indicators selected using Cronbach's alpha	8	Estimated annual cost of a caregiver (based on the avg hourly wage in Italy) Source: ISTAT	4176.00	0%	33,408.00
Orthopedists, orthopedic workshops, healthcare system, INAIL	Offer with higher quality standards	All indicators selected using Cronbach's alpha	8	Saving costs resulting from the pricing difference of similar offerings (Michelangelo) Source: IIT	28,500.00	50%	114,000.00
	Greater attractiveness and/or increased reputation	No. of appearances in press	536	Cost of an article published in national newspapers and periodicals with a circulation of up to 250,000 copies Source: Tariffario ordine dei giornalisti	159.00	0%	85,224.00
				Total present value			461,583.52
				Social return			3.11

Table 3. Outcomes and the measurement of impact on stakeholders.

Patients, the main beneficiaries

Outcomes, indicators, and quantification

Patient outcomes were defined based on users' expectations regarding the capabilities that myoelectric prostheses should guarantee, and their potential implications[1,16,49]. The first two outcomes presented in Table 3 concern functionality, specifically the performance of the device and the participants' ability to carry out daily activities. These are followed by social outcomes, related to patients' job reintegration and broader social participation. Last outcomes relate to psychosocial dimensions: by enabling more natural gestures and postures, myoelectric prostheses can improve users' appearance[50], facilitate social interactions, and contribute to higher self-esteem. Furthermore, thanks to advanced functionality and anthropomorphic design, advanced prostheses can foster a sense of embodiment[51–53], meaning that users increasingly perceive the prosthesis as part of their body rather than as an external tool.

After identifying the outcomes, it is essential to quantify the number of participants in the clinical trial who have experienced them.

For certain outcomes, a synthetic index was already available. Specifically, for the outcome "Restore over 80% of the functionality of a real hand", we utilized the synthetic index from the SHAP functional test. The SHAP functional test evaluates hand functionality through 12 abstract object tasks and 14 ADLs. The time taken to complete each task, measured in seconds, is entered into a web-based scoring tool, which calculates an overall score called the Index of Function (IoF), providing a comprehensive measure of hand performance.

For the embodiment outcome, a single indicator was used, derived from item 15 of the ad hoc questionnaire specifically designed for the project. This questionnaire item, "*I felt as if the robotic hand was part of me, incorporated into my person rather than as a tool*", was rated on a 1-5 Likert scale, where 1 indicates strong disagreement and 5 indicates strong agreement, effectively assessing the patient's sense of embodiment.

For the remaining outcomes, various elementary indicators were derived from different items included in the questionnaires administered to patients during the clinical trial. The selection of these items for each outcome was carried out in collaboration with the Hannes development team and the clinical trial designers. As detailed in the Materials and methods section, when multiple indicators were used to measure a single outcome, normalization was applied to ensure comparability across different scales. Indicator polarity was also adjusted so that higher values consistently represented more favorable outcomes.

Given that the selection of indicators involves an element of subjectivity, empirical criteria were applied to ensure objectivity. In particular, we employed two statistical methods - item–scale correlation and Cronbach's

Outcome	No. of elementary indicators	Cronbach's alpha
Possibility of performing ADLs and improved functional independence	12	0.845
Job reintegration	4	0.864
Social reintegration	4	0.918
Increased self-esteem	5	1.000
Offer with higher quality standards	10	0.944

Table 4. Number of elementary indicators and Cronbach's alpha of each patient outcome. A detailed enumeration of the selected items, from which elementary indicators were derived, is provided in Appendix A of the online Supplementary material

Outcome	Indicator	Target value
Restore over 80% of functionality of a real hand	Synthetic index IoF (SHAP)	0.76
Possibility of performing ADLs and improved functional independence	All indicators selected using Cronbach's alpha	0.75
Job reintegration	All indicators selected using Cronbach's alpha	0.75
Social reintegration and reduction of social isolation	All indicators selected using Cronbach's alpha	0.75
Embodiment	Indicator ADHOC_15	0.75
Increased self-esteem	All indicators selected using Cronbach's alpha	1
Offer with higher quality standards	All indicators selected using Cronbach's alpha	0.7

Table 5. Target values of each outcome selected on the basis of response modes.

alpha - to verify that all selected items were appropriately aligned with the intended construct and demonstrated satisfactory internal consistency.

This approach was applied to all outcomes defined by multiple elementary indicators, specifically: "Possibility of performing ADLs and improved functional independence", "Job reintegration", "Social reintegration and reduction of social isolation", "Increased self-esteem", and "Offer with higher quality standards". Table 4 summarizes the number of indicators and Cronbach's alpha for each outcome, with all values exceeding the reliability threshold of 0.7.

Following the selection of elementary indicators, a synthetic index was constructed for each outcome by averaging the normalized values of the indicators. Thresholds for achieving each outcome, derived from the response scales, are presented in Table 5.

For the first outcome, "Restore over 80% of the functionality of a real hand", the threshold was derived from the literature on the Southampton Hand Assessment Procedure (SHAP). SHAP indicates that non-disabled hands typically achieve an Index of Function (IoF) score of 95–100%. Therefore, a threshold of 0.76 was selected, representing 80% of the lower end of this range (0.80 * 0.95 = 0.76).

A threshold of 0.75 was established for "Possibility of performing ADLs and improved functional independence", "Job reintegration", "Social reintegration and reduction of social isolation", and "Embodiment" outcomes. The elementary indicators for these outcomes used five-point response scales (0, 0.25, 0.5, 0.75, and 1) after normalization.

For "Increased self-esteem" a threshold of 1 was used, reflecting the uniformly high scores reported by all patients for both Hannes and their regular prosthesis.

The "Offer with higher quality standards" outcome used a threshold of 0.7, considering its diverse item scales: three-point (0, 0.5, 1), five-point (0, 0.25, 0.5, 0.75, 1), and a ten-point scale for overall patient satisfaction.

The number of patients experiencing each outcome was determined by counting those exceeding the respective threshold. To ensure a conservative and credible analysis, we also considered counterfactuals, such as patients who would likely have experienced similar benefits using their regular prostheses, by applying deadweight percentages. Attribution and displacement coefficients were not considered necessary in this context, as the effects can be directly attributed to the project due to the strict eligibility and inclusion criteria applied to the clinical trial participants, and no substitution effects are expected.

The results emerging from the clinical trial, presented in Table 3, illustrate that Hannes improved participants' ability to perform daily activities, thereby fostering greater independence. This result is consistent with the findings of Laffranchi et al.[20] and Semprini et al.[54]. Socially, the device contributed to job reintegration, helping patients overcome isolation and engage in community or recreational activities, such as sports. Additionally, Hannes improved users' perceived appearance and social engagement, which in turn elevated self-esteem. The sense of embodiment, reported by many participants, can be attributed to the advanced human-like design and grasping behavior of the prosthesis[55].

Monetary valuation approach

Different financial proxies, particularly for intangible outcomes, were initially explored to approximate social value, as direct measurement is often infeasible[56].

The financial proxy of the first outcome, which aimed to restore at least 80% of natural hand functionality, was based on INAIL compensation awarded to workers who experience a loss of psychophysical integrity resulting from a workplace accident or occupational disease, as defined in Article 13 of Legislative Decree No. 38/2000. Because INAIL assigns a 70–80% disability rating for forearm in the middle third or complete hand loss, compensation was calculated at 75%. In addition to the subject's permanent disability percentage, the calculation considers age (using the sample average of 49), job classification ("industry"), annual salary (€27,000, based on 2023 ISTAT data), and number of dependents (two, representing a spouse and child, based on 2021 ISTAT data, which indicated an average of 1.25 children per woman).

The financial proxy for the second outcome, focusing on the ability to perform ADLs and increased independence, was derived from the cost savings associated with hiring a caregiver. The annual caregiver cost was calculated using a minimum wage of €9 per hour, assuming 24 hours per week (see Pinelli et al.,[57]).

For job reintegration, the proxy used was the monthly INPS allowance granted to individuals with a recognized partial reduction in work capacity, falling below the legal income thresholds. This allowance, paid by INPS for 13 months annually, amounts to €313.97 in 2023.

To monetize the outcome related to patients' social reintegration, such as returning to recreational or sports activities, we adopted a proxy based on the annual cost of membership in a team sport club. This approach is grounded in the idea that participation in such activities reflects a concrete form of social engagement and inclusion. This financial proxy has already been used in literature, specifically in a study by Bellucci et al.[58], in which the authors adopted an annual cost of team sports membership (€576, ISTAT 2016), which we have adjusted for inflation to €683.71.

To determine a financial proxy for embodiment, literature on prosthesis abandonment was consulted. High abandonment rate in upper-limb prosthesis users[59–61] is influenced by various factors, including individual characteristics, level of amputation[59], type of prosthesis[62], and the adequacy of training. Social and psychological factors also play a crucial role, especially in how well users can integrate the device into their body image and seamlessly incorporate it into their daily lives. The difficulty in achieving this integration may lead to abandonment of the device[63]. Several studies—such as those conducted by Biddiss et al.[59], Smail et al.[60], and Salminger et al.[61]—identify key reasons for prosthesis abandonment, which can be grouped into three main categories: (1) lack of comfort (e.g., excessive weight or temperature), (2) limited functionality (e.g., inadequate control or sensory feedback), and (3) poor aesthetics. Since embodiment is facilitated when a prosthesis successfully fulfills a dual role, supporting both appearance and functional performance[64], we argue that increased embodiment reduces the likelihood of abandonment. Therefore, the cost savings from avoided prosthesis replacement represent a suitable financial proxy for this outcome. The monetary value was determined by multiplying the cost of a high-technology prosthesis by the observed rejection rate of 12.5%. This rate reflects the proportion of patients who reached a 0.75 embodiment threshold with the Hannes prosthesis but did not achieve this threshold with their regularly used prosthesis. The INAIL price list sets the cost of replacing a failed prosthesis with a more advanced model, such as the Michelangelo hand (Ottobock), at €26,473.30.

Finally, the significant boost in self-esteem experienced by Hannes users was financially valued using the average cost of ten counseling sessions designed to improve self-confidence and self-esteem.

This SROI analysis, based on data from the clinical trial (which directly involved only patients), represents an initial assessment of the project's social impact. While limited by the available data, it identifies other relevant stakeholders and estimates their potential outcomes and social impact.

Additional stakeholders—outcomes, indicators, quantification and monetary valuation approach

Caregivers are a key stakeholder group. Hannes significantly enhances the autonomy of limb-difference subjects[20,54], thereby reducing their need for assistance with essential activities such as cleaning or meal preparation. To estimate the potential reduction in caregiver burden, we relied on the outcome "Possibility of performing ADLs and improved functional independence". In this context, 8 out of 11 patients achieved the target value of 0.75, indicating increased independence. These eight patients were assumed to no longer require caregiver support, allowing corresponding cost savings to be calculated. The time commitment of professional and non-professional caregivers was assessed using Italy's average gross hourly wage (€14.5, ISTAT) and caregiver workload estimates based on Law 104, which provides for 3 days of paid leave per month. The enhanced ability of users to perform activities of daily living (ADLs) generated benefits for both patients and caregivers. For patients, the benefit is greater independence, and the proxy is measured as the estimated annual cost of hiring a caregiver. For caregivers, the proxy captures the value of time saved or stress reduced, estimated using the cost of informal or professional care. Consequently, we employed the same indicator to measure two distinct outcomes with separate financial proxies. This approach is consistent with the SROI methodology, which allows the same event to generate different outcomes for different stakeholders, provided that stakeholders are clearly distinguished, and proxies reflect their unique perspectives.

Other stakeholders include orthopedists, orthopedic workshops, local health authorities (ASL), and INAIL. Adopting Hannes could improve the quality standards of their services while enhancing market attractiveness and reputation. Although IIT, as a private foundation, cannot directly market products, Hannes has CE certification, complying with Directive 93/42/EEC and EU safety standards, making it a valuable offering for these stakeholders.

For the "Offer with higher quality standards" outcome, we used the mean score from patient questionnaires that assessed the quality of the Hannes device. Eight of eleven patients scored above the 0.7 threshold. The monetary value was estimated by calculating the cost savings from the price difference of similar offers. Specifically, the comparison was made with the best-in-class Michelangelo prosthesis (€42,000).

Stakeholder	Outcome	Drop-off	Impact calculation year 1	Impact calculation year 2	Impact calculation year 3	Impact calculation year 4	Impact calculation year 5
Patients	Restore over 80% of functionality of a real hand	5%	171,192.20	162,632.59	154,500.96	146,775.91	139,437.12
	Possibility of performing ADLs and improved functional independence	5%	43,200.00	41,040.00	38,988.00	37,038.60	35,186.67
	Job reintegration	5%	4081.61	3877.53	3683.65	3499.47	3324.50
	Social reintegration and reduction of social isolation	5%	3418.55	3247.62	3085.24	2930.98	2784.43
	Embodiment	5%	3309.16	3,143.70	2,986.52	2837.19	2695.33
	Increased self-esteem	5%	3750.00	3562.50	3384.38	3,215.16	3054.40
Caregivers	Reducing caregiver burden	5%	33,408.00	31,737.60	30,150.72	28,643.18	27,211.02
Orthopedists Orthopedic workshops Healthcare system INAIL							
	Offer with higher quality standards	0%	114,000.00	0	0	0	0
	Greater attractiveness and/or increased reputation	0%	85,224.00	0	0	0	0
	Present value per year		461,583.52	239,080.62	217,867.23	198,536.09	180,920.17
	Social return per year		3.11	1.61	1.47	1.34	1.22
	Social return 5 years		8.74				

Table 6. Outcomes and the measurement of impact on stakeholders over five years.

The increased facility attractiveness and reputation were assessed by considering the savings in advertising costs resulting from media exposure. Using the number of press articles mentioning Hannes (536, per IIT's communication office) as an indicator, the monetary value was derived using a cost-per-article from the online price list of journalists' tariff (refer to the following online document: Journalists' Tariff).

The final key stakeholders are IIT and INAIL. As project funders and implementers, IIT and INAIL played a pivotal role in developing and deploying Hannes. Additionally, they clearly understand the changes experienced by both direct and indirect beneficiaries.

Based on actual costs incurred for small series production (11 units), the average production cost per prosthesis was €13,500. More precisely, these costs include expenses for the purchase of mechanical and electronic components, as well as accessory and commercial parts related to the wrist and hand, in addition to labor costs. With 11 prostheses produced for the clinical trial, the total investment amounted to €148,500.

We can assume that with larger-scale production, the costs of the various prosthetic components would decrease, thereby potentially increasing the SROI value.

Impact calculation

Table 3 shows that Hannes generates almost €461,500.00 in social value for various stakeholders against an initial investment of €148,500.00, yielding an SROI ratio of 3.11:1 for the first year. This ratio was calculated by comparing the monetary value of social benefits with project costs, using a conservative approach to avoid overestimation. The results confirm a significant social return on investment.

The INAIL center estimates the lifespan of a myoelectric prosthesis for upper limb amputations at five years (Annex No. 4 to Resolution 92009). Short-term outcomes, such as those related to orthopedists, workshops, the healthcare system, and INAIL, are assigned a one-year duration. Outcomes directly related to Hannes used, with medium-to-long-term effects, are assigned a five-year duration. Because some outcomes extend beyond a single year, it was crucial to set a drop-off to account for diminishing impacts over time. An annual drop-off rate of 5% was chosen by the IIT development team to account for possible wear and tear, even though they expect the prosthesis to maintain stable performance throughout its 5-year lifespan. Moreover, despite its limited service life, the prosthesis is supported by ongoing maintenance, warranty, and assistance, further ensuring sustained functionality. This rate is considered conservative because certain social benefits - such as improved user skills, increased autonomy, and enhanced performance - may grow over time as users become more experienced and confident with the prosthesis. This decision is also supported by evidence from the clinical study, which showed consistently high levels of use and user engagement with the Hannes prosthesis.

If the time horizon under consideration exceeds one year, SROI requires the application of a discount rate to account for the time value of money. This rate facilitates the comparison of costs and benefits across different periods. Determining an appropriate discount rate requires consideration of several factors, including prevailing market interest rates, project-specific risks, and broader economic expectations. It is worth noting that the discount rate is subject to variability depending on the specific context and sector. To provide a realistic estimate, we adopted a discount rate of 4.25%, based on the coupon rate of low-risk investments, exemplified by BTPs (Buoni del Tesoro Poliennali).

Table 6 reports the values of the impact calculation for each year. Starting from the second year, all impacts were adjusted by applying an annual drop-off rate of 5% to account for the potential reduction in outcomes over time. Furthermore, the Present Value for each year was calculated by dividing the sum of all impacts in t by $(1+r)^t$, where r is the discount rate (4.25%) and t is the corresponding year. Over five years, the total cumulative impact value reaches €1,297,318.75 with an SROI ratio of 8.74. This underscores Hannes' value in delivering direct benefits to patient well-being and indirect benefits to other stakeholders.

To estimate the counterfactual scenario, we calculated the deadweight among current myoelectric prosthesis users. Deadweight represents the proportion of outcomes that would have been achieved with existing prostheses, independent of Hannes. This calculation is based on a comparison of pre- and post-Hannes questionnaire data. Expanding the comparison to include upper-limb amputees not using myoelectric prostheses reduces deadweight to 0%, resulting in an SROI of 4.61:1. Considering the full project period, the SROI increases to 12.58:1. This demonstrates that Hannes' benefits grow over time, confirming its substantial long-term impact.

As noted, SROI reliability can be influenced by subjective choices in selecting indicators and assigning financial proxies. To mitigate the subjectivity in indicator selection, we employed an empirical approach, using item-scale correlation and Cronbach's alpha coefficient to ensure that indicators accurately measured the same underlying or latent construct.

Sensitivity analyses were performed by testing different financial proxies for the same outcome. Specifically, we calculated the SROI for all conceivable combinations of these financial proxies, thereby defining a range within which the index may vary. The analysis, based on the lowest and highest values for each financial proxy, showed that the SROI remained consistently positive, ranging from 2.92 to 3.20 for the first year and from 7.94 to 9.14 over five years, demonstrating the robustness and stability of the results. The SROI ratio of 8.74 reflects a balanced and cautious approach, aligning with SROI principles and ensuring a scientifically effective representation of the project's social and economic impact. Further sensitivity analysis was conducted by adjusting thresholds used to determine the number of individuals experiencing a particular outcome. The sensitivity analysis revealed that, despite variations in threshold values of up to $\pm 5\%$, the SROI estimates consistently remained positive and relatively close to the reference scenario values, thereby confirming the robustness and reliability of the findings. The results of these sensitivity analyses are detailed in Appendix B of the online Supplementary material.

Discussion and conclusions

This study evaluates the socio-economic impact of Hannes, a prosthetic hand with biomimetic properties closely resembling a natural hand, using a Social Return on Investment (SROI) analysis. This methodology enabled the estimation of both the costs and benefits generated by Hannes, considering a wide range of impacts. The findings demonstrate Hannes' transformative potential for individuals with limb difference and their stakeholders.

Through a clinical trial conducted by IIT and INAIL, we collected data from 11 participants who evaluated Hannes against their regularly used myoelectric prostheses. Validated tests and questionnaires offered a holistic view of the impacts experienced by patients and their immediate networks. The analysis revealed that Hannes generates significant social value, with an SROI ratio of 8.74:1, meaning that every €1 invested yields €8.74 in returns. The most notable benefits were observed among patients, including improved functionality, autonomy, physical activity, self-esteem, and social inclusion. These outcomes directly translate into enhanced quality of life, reduced reliance on caregiving, and increased opportunities for job reintegration.

Beyond individual benefits, Hannes has far-reaching implications for economic health. The reduction in caregiving needs alleviates not only the physical and emotional burden on caregivers but also the economic opportunity costs associated with unpaid care. This allows caregivers to re-enter the workforce or redirect their time to other pursuits, contributing to overall economic productivity. For patients, job reintegration highlights the potential of advanced prostheses to support labor market participation, reducing dependence on social welfare systems and fostering economic stability.

The findings also provide critical insights for policymakers, emphasizing the value of investing in advanced assistive technologies like Hannes. By addressing both physical and psychosocial challenges, the prosthesis aligns with value-based healthcare models that prioritize outcomes over costs. Its ability to foster social integration and reduce inequalities makes it a powerful tool for achieving broader societal goals of equity and inclusion, positioning Hannes as an essential resource for enhancing individual outcomes, public health, and social cohesion.

This work extends the body of literature on SROI analysis in healthcare, particularly in evaluating health technology designed to improve the quality of life for individuals with disabilities. While SROI has been used to assess chronic conditions such as cancer, diabetes, and dementia[65–77], its application to robotic rehabilitation technologies remains limited.

To our knowledge, this study represents the first application of the SROI methodology to a robotic prosthetic hand. In the literature, some studies have applied SROI to evaluate the impact of other assistive technologies. For example, Hutchinson et al.[78] investigated home automation systems for people with disabilities; however, this study differs from our work, as it focused on a suite of technologies aimed at improving the habitability and functionality of homes rather than evaluating a single device.

Other works, such as those by Di Francesco et al.[79] and Pinelli et al.[57], analyzed the impact of specific robotic devices, an ankle-foot orthosis and an upper-limb rehabilitation exoskeleton, respectively.

In contrast to these prior studies, our evaluation relied on real-world data from a clinical trial, rather than on hypothetical scenarios or literature-based assumptions. We also improved data reliability by employing internationally validated clinical and psychosocial questionnaires, rigorously defining outcome thresholds to determine when a change is significant, and clearly specifying coefficients like deadweight. Furthermore, we avoided subjective financial proxies, such as willingness to pay, thereby increasing the robustness and reproducibility of our results.

Methodologically, this study demonstrates the strengths of SROI in capturing diverse impacts among stakeholders while combining quantitative data with qualitative insights. Inherent limitations, such as the subjectivity in selecting financial proxies and indicators, were addressed through rigorous empirical methods, including item-scale correlations and Cronbach's alpha. Sensitivity analyses further validated the findings by testing alternative scenarios. Despite these strengths, the small sample size and the Italian context specificity may limit the generalizability of the conclusions, although the overall methodological framework remains adaptable and can be replicated in other contexts to inform local policy and funding decisions.

In conclusion, this study represents a pioneering application of SROI analysis to a robotic rehabilitation prosthesis, offering valuable insights into the economic and societal impacts of advanced healthcare technologies. Hannes not only delivers substantial benefits to patients but also generates indirect gains for caregivers, healthcare providers, and society as a whole. By addressing the physical, psychological, and social challenges of disability, the prosthesis demonstrates its potential to drive meaningful improvements in both individual and societal well-being.

These findings underscore the importance of comprehensive impact assessments in guiding health policy decisions and illustrate how such assessments can be effectively implemented. By measuring social value, policymakers and managers can make evidence-based, transparent, and accountable decisions that optimize resource allocation and strengthen public trust. The Hannes case demonstrates how integrating these assessments can maximize societal benefits, especially when incorporating assistive technologies into care pathways. Furthermore, it can help attract investments and enhance internal decision-making processes, as highlighted by Bellucci et al.[80].

Future research should expand upon these findings by including larger, more diverse subjects and directly engaging stakeholders to validate and strengthen the results. It should also explore the scalability of robotic prostheses to ensure broader access and contribute to more equitable healthcare systems.

Data availability

The datasets generated and analysed during the current study are not publicly available due to their sensitivity but are available from the corresponding author upon reasonable request.

Received: 28 March 2025; Accepted: 8 August 2025
Published online: 25 September 2025

References

1. Cordella, F. et al. Literature review on needs of upper limb prosthesis users. *Front. Neurosci.* **10**, 209 (2016).
2. Roşca, A. C., Baciu, C. C., Burtăverde, V. & Mateizer, A. Psychological consequences in patients with amputation of a limb. an interpretative-phenomenological analysis. *Front. Psychol.* **12**, 537493 (2021).
3. Segura, D., Romero, E., Abarca, V. E. & Elias, D. A. Upper limb prostheses by the level of amputation: A systematic review. *Prosthesis* **6**, 277–300 (2024).
4. Vujaklija, I., Farina, D. & Aszmann, O. C. New developments in prosthetic arm systems. Orthopedic research and reviews 31–39 (2016).
5. Kristjansdottir, F., Dahlin, L. B., Rosberg, H.-E. & Carlsson, I. K. Social participation in persons with upper limb amputation receiving an esthetic prosthesis. *J. Hand Therapy* **33**, 520–527 (2020).
6. Mitchell, S., Andrews, L. & Engward, H. Examining the effects of acquired limb loss on the family network: A grounded theory study. *Disabil. Rehabil.* **44**, 745–753 (2022).
7. Efanov, J., Tchiloemba, B., Izadpanah, A., Harris, P. & Danino, M. A review of utilities and costs of treating upper extremity amputations with vascularized composite allotransplantation versus myoelectric prostheses in canada. *JPRAS open* **32**, 150–160 (2022).
8. Ministero della Salute. Statistiche sull'incidenza delle amputazioni in italia: analisi dati sdo del ministero della salute anni 2012-2021 (2023). Direzione centrale assistenza protesica e riabilitazione, settore comunicazione e marketing.
9. Fahrenkopf, M. P., Adams, N. S., Kelpin, J. P. & Do, V. H. Hand amputations. Eplasty **18**, ic21 (2018).
10. Shahsavari, H., Ghiyasvandian, S., Matourypour, P. & Golestannejad, M. R. Medical research council framework for designing and evaluating a re-integration into life care plan in patients following upper limb amputation in iran: An interventional study. *J. Vascular Nur.* **40**, 86–91 (2022).
11. Damerla, R., Qiu, Y., Sun, T. M. & Awtar, S. A review of the performance of extrinsically powered prosthetic hands. *IEEE Trans. Medical Robotics Bionics* **3**, 640–660 (2021).
12. Geethanjali, P. Myoelectric control of prosthetic hands: State-of-the-art review. Med. Devices: Evidence Res. 247–255 (2016).
13. Widehammar, C., Holmqvist, K. L. & Hermansson, L. Training for users of myoelectric multigrip hand prostheses: A scoping review. *Prosthetics Orthot. Int.* **45**, 393–400 (2021).
14. Parr, J. V. et al. A scoping review of the application of motor learning principles to optimize myoelectric prosthetic hand control. *Prosthet. Orthot. Int.* **46**, 274–281 (2022).
15. Zecca, M., Micera, S., Carrozza, M. C. & Dario, P. Control of multifunctional prosthetic hands by processing the electromyographic signal. Critical Rev. Biomed. Eng. **30** (2002).
16. Marinelli, A. et al. Active upper limb prostheses: A review on current state and upcoming breakthroughs. *Progress Biomed. Eng.* **5**, 012001 (2023).
17. Mendez, V., Iberite, F., Shokur, S. & Micera, S. Current solutions and future trends for robotic prosthetic hands. *Annual Rev. Control, Robotics, Auton. Syst.* **4**, 595–627 (2021).
18. Brack, R. & Amalu, E. H. A review of technology, materials and r &d challenges of upper limb prosthesis for improved user suitability. *J. Orthopaedics* **23**, 88–96 (2021).
19. Marinaccio, A. et al. Predictors of filing claims and receiving compensation in malignant mesothelioma patients. *Health Policy* **124**, 1032–1040 (2020).
20. Laffranchi, M. et al. The hannes hand prosthesis replicates the key biological properties of the human hand. Sci. Robot. **5**, eabb0467 (2020).
21. Grand View Research. Rehabilitation robots market size, share & trends analysis report by type (therapy robots, exoskeleton), by extremity (upper body, lower body), by end-use (hospitals & clinics, senior care facilities, homecare settings), by region, and segment forecasts, 2025 - 2030 (2024).
22. Marinelli, A. et al. Miniature emg sensors for prosthetic applications. In *2021 10th International IEEE/EMBS Conference on Neural Engineering (NER)*, 1022–1025 (IEEE, 2021).
23. Hart, S. G. & Staveland, L. E. Development of nasa-tlx (task load index): Results of empirical and theoretical research. Adv. Psychol. , vol. 52, 139–183 (Elsevier, 1988).
24. Brooke, J. Sus: a "quick and dirty'usability. *Usability Evaluat. Ind.* **189**, 189–194 (1996).
25. Brooke, J. Sus: A retrospective. *J. Usability Stud.* **8**, 29–40 (2013).

26. Gallagher, P. & MacLachlan, M. Development and psychometric evaluation of the trinity amputation and prosthesis experience scales (tapes). *Rehabil. Psychol.* **45**, 130 (2000).
27. Heinemann, A. W., Bode, R. & O'reilly, C. Development and measurement properties of the orthotics and prosthetics users' survey (opus): a comprehensive set of clinical outcome instruments. *Prosthes. Orthot. Int.* **27**, 191–206 (2003).
28. Hudak, P. L. et al. Development of an upper extremity outcome measure: The dash (disabilities of the arm, shoulder, and head). *Am. J. Ind. Med.* **29**, 602–608 (1996).
29. Desrosiers, J., Rochette, A., Hebert, R. & Bravo, G. The minnesota manual dexterity test: Reliability, validity and reference values studies with healthy elderly people. *Canadian J. Occup. Ther.* **64**, 270–276 (1997).
30. Light, C. M., Chappell, P. H. & Kyberd, P. J. Establishing a standardized clinical assessment tool of pathologic and prosthetic hand function: Normative data, reliability, and validity. *Arch. Phys. Med. Rehabil.* **83**, 776–783 (2002).
31. Mathiowetz, V., Volland, G., Kashman, N. & Weber, K. Adult norms for the box and block test of manual dexterity. *Am. J. Occup. Ther.* **39**, 386–391 (1985).
32. Botvinick, M. & Cohen, J. Rubber hands 'feel'touch that eyes see. *Nature* **391**, 756–756 (1998).
33. D'Alonzo, M., Clemente, F. & Cipriani, C. Vibrotactile stimulation promotes embodiment of an alien hand in amputees with phantom sensations. *IEEE Trans. Neural Syst. Rehabilitation Eng.* **23**, 450–457 (2014).
34. Resnik, L. et al. Evaluation of emg pattern recognition for upper limb prosthesis control: A case study in comparison with direct myoelectric control. *J. Neuroeng. Rehabil.* **15**, 1–13 (2018).
35. Paquette, R. et al. Utility of body-powered voluntary opening and closing terminal devices on transradial prostheses. Technol. Innov. 1–12 (2025).
36. Vanclay, F. International principles for social impact assessment. *Impact Assess. Project Appraisal* **21**, 5–12 (2003).
37. Zamagni, S., Venturi, P. & Rago, S. Valutare l'impatto sociale. la questione della misurazione nelle imprese sociali. Impresa Sociale **6**, 77–97 (2015).
38. Emerson, J. & Cabaj, M. *Social return on investment. Making Waves* **11**, 10–14 (2000).
39. Krlev, G., Münscher, R. & Mülbert, K. Social return on investment (sroi): state-of-the-art and perspectives-a meta-analysis of practice in social return on investment (sroi) studies published 2002-2012 (2013).
40. Ashton, K., Parry-Williams, L., Dyakova, M. & Green, L. Health impact and social value of interventions, services, and policies: A methodological discussion of health impact assessment and social return on investment methodologies. *Front. Public Health* **8**, 49 (2020).
41. Perrini, F., Costanzo, L. A. & Karatas-Ozkan, M. Measuring impact and creating change: A comparison of the main methods for social enterprises. *Corporate Governance: Int. J. Bus. Soc.* **21**, 237–251 (2021).
42. Clark, C. & Rosenzweig, W. *Double bottom line project report* (University of California, Berkeley, 2004).
43. Mishan, E. J. & Quah, E. Cost-benefit analysis (Routledge, 2020).
44. Nicholls, J., Lawlor, E., Neitzert, E. & Goodspeed, T. A guide to social return on investment (2012).
45. King, N. Making the case for sport and recreation services: The utility of social return on investment (sroi) analysis. *Int. J. Public Sector Manag.* **27**, 152–164 (2014).
46. Mazziotta, M. & Pareto, A. Synthesis of indicators: The composite indicators approach. Complexity in society: From indicators construction to their synthesis 159–191 (2017).
47. Cronbach, L. J. Coefficient alpha and the internal structure of tests. Psychometrika **16**, 297–334 (1951).
48. Nunnally, J. C. Psychometric theory: 2d Ed (McGraw-Hill, 1978).
49. Peerdeman, B. et al. Myoelectric forearm prostheses: State of the art from a user-centered perspective. *J. Rehabil. Res. Develop.* **48**, 719–738 (2011).
50. Luchetti, M., Cutti, A. G., Verni, G., Sacchetti, R. & Rossi, N. Impact of michelangelo prosthetic hand: Findings from a crossover longitudinal study. J. Rehabil. Res. & Development **52** (2015).
51. Longo, M. R., Schüür, F., Kammers, M. P., Tsakiris, M. & Haggard, P. What is embodiment? a psychometric approach. *Cognition* **107**, 978–998 (2008).
52. Gouzien, A. et al. Reachability and the sense of embodiment in amputees using prostheses. *Sci. Rep.* **7**, 4999 (2017).
53. Zbinden, J., Lendaro, E. & Ortiz-Catalan, M. Prosthetic embodiment: systematic review on definitions, measures, and experimental paradigms. *J. NeuroEng. Rehabil.* **19**, 37 (2022).
54. Semprini, M. et al. Clinical evaluation of hannes: Measuring the usability of a novel polyarticulated prosthetic hand. In Tactile Sensing, Skill Learning, and Robotic Dexterous Manipulation, 205–225 (Elsevier, 2022).
55. Caserta, G. Evaluation and improvement of the embodiment of an upper limb prosthesis: the hannes system (2019).
56. Rauscher, O., Schober, C. & Millner, R. Social impact measurement und social return on investment (sroi)-analysis. New Methods Econ. Evaluat. (2012).
57. Pinelli, M., Manetti, S. & Lettieri, E. Assessing the social and environmental impact of healthcare technologies: Towards an extended social return on investment. *Int. J. Environ. Res. Public Health* **20**, 5224 (2023).
58. Bellucci, M., Nitti, C., Chimirri, C. & Bagnoli, L. Rendicontare l'impatto sociale. metodologie, indicatori e tre casi di sperimentazione in toscana. Manag. Control (2019).
59. Biddiss, E. A. & Chau, T. T. Upper limb prosthesis use and abandonment: A survey of the last 25 years. *Prosthet. Orthot. Int.* **31**, 236–257 (2007).
60. Smail, L. C., Neal, C., Wilkins, C. & Packham, T. L. Comfort and function remain key factors in upper limb prosthetic abandonment: Findings of a scoping review. *Disability Rehabil.: Assistive Technol.* **16**, 821–830 (2021).
61. Salminger, S. et al. Current rates of prosthetic usage in upper-limb amputees-have innovations had an impact on device acceptance?. *Disabil. Rehabil.* **44**, 3708–3713 (2022).
62. Resnik, L. et al. Advanced upper limb prosthetic devices: Implications for upper limb prosthetic rehabilitation. *Arch. Phys. Med. Rehabil.* **93**, 710–717 (2012).
63. Dornfeld, C. et al. Is the prosthetic homologue necessary for embodiment?. *Front. Neurorobot.* **10**, 21 (2016).
64. Saradjian, A., Thompson, A. R. & Datta, D. The experience of men using an upper limb prosthesis following amputation: Positive coping and minimizing feeling different. *Disabil. Rehabil.* **30**, 871–883 (2008).
65. Pazderka, H. et al. Five year cost savings of a multimodal treatment program for child sexual abuse (csa): A social return on investment study. *BMC Health Services Res.* **22**, 892 (2022).
66. Merino, M. et al. Optimising the management of patients with multiple myeloma in spain: A measurement of the social return on investment. *Euro. J. Cancer Care* **31**, e13706 (2022).
67. Daems, R., Maes, E., Mehra, M., Carroll, B. & Thomas, A. Pharmaceutical portfolio management: Global disease burden and corporate performance metrics. *Value Health* **17**, 732–738 (2014).
68. Jalkanen, K. et al. Pharmacy-based screening to detect persons at elevated risk of type 2 diabetes: A cost-utility analysis. *BMC Health Serv. Res.* **21**, 1–11 (2021).
69. Merino, M. et al. The social return on investment of a new approach to heart failure in the spanish national health system. *ESC Heart Failure* **7**, 131–138 (2020).
70. Hartfiel, N., Gladman, J., Harwood, R. & Tudor Edwards, R. Social return on investment of home exercise and community referral for people with early dementia. *Gerontol. Geriatric Med.* **8**, 23337214221106840 (2022).
71. Jones, C., Windle, G. & Edwards, R. T. Dementia and imagination: A social return on investment analysis framework for art activities for people living with dementia. *Gerontologist* **60**, 112–123 (2020).

72. Prendergast, L. et al. 'it was just-everything was normal': Outcomes for people living with dementia, their unpaid carers, and paid carers in a shared lives day support service. *Aging Mental Health* **27**, 1282–1290 (2023).
73. Willis, E., Semple, A. C. & de Waal, H. Quantifying the benefits of peer support for people with dementia: A social return on investment (sroi) study. *Dementia* **17**, 266–278 (2018).
74. Makanjuola, A. et al. A social return on investment evaluation of the pilot social prescribing emotionmind dynamic coaching programme to improve mental wellbeing and self-confidence. *Int. J. Environ. Res. Public Health* **19**, 10658 (2022).
75. Piper, S. et al. Implementing a digital health model of care in australian youth mental health services: protocol for impact evaluation. *BMC Health Serv. Res.* **21**, 1–9 (2021).
76. Foster, A. et al. Impact of social prescribing to address loneliness: A mixed methods evaluation of a national social prescribing programme. *Health Social Care Commun.* **29**, 1439–1449 (2021).
77. DiLorenzo, D. J. Societal return on investment may greatly exceed financial return on investment in neurotechnology-based therapies: A case study in epilepsy therapy development. Surg. Neurol. Int. **12** (2021).
78. Hutchinson, C., Cleland, J., Williams, P. A., Manuel, K. & Laver, K. Calculating the social impact of home automation for people with disability: A social return on investment study. *Australian Occup. Ther. J.* **71**, 956–966 (2024).
79. Di Francesco, A., Pinelli, M., Lettieri, E., Toletti, G. & Galli, M. Towards a more inclusive society: The social return on investment (sroi) of an innovative ankle-foot orthosis for hemiplegic children. *Sustainability* **15**, 4361 (2023).
80. Bellucci, M., Nitti, C., Franchi, S., Testi, E. & Bagnoli, L. Accounting for social return on investment (sroi) the costs and benefits of family-centred care by the ronald mcdonald house charities. *Social Enterprise J.* **15**, 46–75 (2019).

Acknowledgements
We would like to express our gratitude to the entire Rehab Technology Lab team at the Italian Institute of Technology. The Open University Affiliated Research Centre at Istituto Italiano di Tecnologia (ARC@IIT) is part of the Open University, Milton Keynes MK7 6AA, United Kingdom.

Author contributions
S.P. Conceptualization, Methodology, Software, Formal analysis, Data Curation, Writing - Original Draft, Visualization, G.C. Participants Recruitment, Data Collection, Clinical Trial Execution - Review & Editing, L.D.M. Review & Editing, Supervision, N.B. Participants Recruitment, Data Collection, Clinical Trial Execution - Review & Editing, E.d.B. Conceptualization, Writing - Review & Editing, Supervision. All authors reviewed the manuscript.

Funding
Sara Preti conducted this research as part of her PhD in Economics and Political Economy at the University of Genoa. The project was partially supported by the Italian Institute of Technology, which provided funding through Sara Preti's PhD scholarship and by the Istituto Nazionale Assicurazione Infortuni sul Lavoro, under grant agreements PPR AS 1/1 and PR19-PAS-P1.

Declarations

Competing interests
The authors declare no competing interests.

Ethical approval
The clinical study was conducted in collaboration with the Prosthetic Centre of INAIL (Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro, the Italian workers' compensation system) in Vigorso di Budrio, Italy. It received approval from the Ethics Committee of Area Vasta Emilia Centro (Protocol code: CP-PPRAS1/1-03).

Consent to participate
All participants provided written informed consent prior to the study, which followed the principles of the Declaration of Helsinki.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-15652-y.

Correspondence and requests for materials should be addressed to S.P.