Clinical and economic effectiveness of smart home technologies for independent living of older adults: A literature review and research agenda

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Abstract— The global aging of the population is increasing the need for innovative technological solutions, such as the Ambient Assisted Living (AAL) environment, which enables older adults to maintain their independence and live at home. The purpose of this review article is to synthesize empirical evidence on the impact of smart home technologies on the functional independence of older adults and to assess their economic sustainability. An analysis of ten selected studies reveals that the effectiveness of these systems is not universal and depends on their level of technical sophistication and the specific characteristics of the target population. Key findings show that advanced multimodal systems supported by artificial intelligence deliver significant clinical benefits, including improved assessments of activities of daily living (ADL) and a reduction in falls by up to 42%. At the same time, such solutions demonstrate high cost-effectiveness by preventing hospitalizations and postponing institutional care. In contrast, basic assistance systems do not always show measurable clinical improvements or economic savings in more demanding user groups, such as people with dementia. The successful implementation of AAL technologies in practice requires addressing challenges such as privacy protection, the digital divide, and the need for user technical training. The importance of this work lies in identifying the factors that distinguish effective interventions from ineffective ones, which provides a basis for the development of user-oriented policies. Technology must be understood as a complementary element of a comprehensive care ecosystem that respects the autonomy and dignity of older adults.

Keywords— AAL, smart home, independent living for older people, gerontechnology, activities of daily living.

I. Introduction

The global aging of the population is one of the greatest demographic challenges of our time, requiring innovative approaches to support older adults' independent living at home. Maintaining independence in familiar surroundings is not only a strong personal preference for most older adults but also a key way to reduce the financial burden on healthcare systems associated with institutional care [1]. European demographic trends indicate that in the coming decades, the proportion of people over age 80 will grow the fastest, requiring a complete overhaul of existing long-term care models toward digitalization and automation. This means that technology will no longer be just an option but a prerequisite for the sustainability of social welfare systems. Living at home allows older adults to maintain social ties, which is essential for their psychological well-being and active participation in society [2], [3]. Smart home technologies are therefore being developed worldwide in response to advancing technology, rising care costs, and the desire for autonomy in the home of one's choice [4].

Smart homes are advanced technological platforms that integrate sensor systems to continuously monitor user well-being and safety. These are dwellings equipped with functions that detect critical situations, assist with memory, and monitor environmental parameters in order to improve quality of life [5]. Modern solutions for ambient assisted living (AAL) and telecare enable continuous monitoring of users' physical and mental condition via built-in biosensors and computer technologies [6], [7]. Such solutions, which connect homes with monitoring centres, are increasingly recognised in European policies as a key tool for ageing in the home environment [8].

Despite the rapid development of smart home technologies, current empirical evidence of their actual effectiveness in real-world settings remains inconsistent. The main knowledge gap is the lack of a clear distinction between the technical accuracy of the systems and their actual impact on clinical outcomes and economic sustainability in different elderly populations. Most existing studies focus solely on technical accuracy under controlled conditions, neglecting the human aspect and long-term economic sustainability in real-world environments. The purpose of this review article is to critically evaluate how AAL solutions affect the daily independence of older people in independent accommodation. The analysis is based on a qualitative synthesis of ten representative empirical studies published between 2021 and 2025. The studies were selected using the PECO framework to illustrate the spectrum from technical validation in a laboratory environment to clinical and economic evaluations in a real-world setting. This approach bridges the gap between engineering and gerontological perspectives. The value of this contribution lies in identifying key factors that distinguish effective technological interventions from ineffective ones, an essential basis for developing user-oriented care and gerontechnology policies.

II. Methodology

A. Literature search strategy

To systematically search for literature, we used a structured approach based on the PECO framework (Table 1). This framework helped us clearly define the research question and develop a comprehensive search strategy.

TABLE I. PECO FRAMEWORK

PECO Category	Description
P - Population	Older adults in independent living facilities
E - exposure	Automation technologies in smart homes
C - comparison	Traditional living without automation
O - outcomes	Level of independence

The population (P) consisted of older adults residing in independent living facilities. Exposure (E) represents automation technologies in the context of smart homes, including assisted living environments, gerontechnology, and home automation. The comparison (C) covers traditional living without automation or standard care. The outcomes (O) focus on the level of independence, functional status, and quality of life of older adults.

Based on the PECO framework, we developed a comprehensive set of search terms that includes synonyms for each concept linked by Boolean operators (OR for synonyms, AND for linking concepts). For the population, we used terms such as "aged", "elder*", "senior*", "older adult*", and terms for living environments ("independent living", "assisted living", "aging in place"). For technologies, we included "smart home*", "ambient assisted living", "AAL", "gerontechnology", "home automation", and related terms. For comparison, we used "usual care", "standard care", "control* group*", and for results, "independence", "autonomy", "functional status", "ADL", "IADL", and "quality of life".

We conducted a systematic literature search on 17 November 2025 in the Web of Science database using the following search query: (P) AND (E) AND (C) AND (O). The initial search returned 70 hits.

B. 2.2 Inclusion and exclusion criteria

Inclusion criteria: original research studies with empirical data, participants aged 65 or older, living in independent accommodation or a home environment (institutional care excluded), an intervention involving AAL technologies or smart home systems, measurement of independence, functional status, or ADL, a control or comparison group, publication between 1 January 2021 and 17 November 2025, and full-text availability.

Exclusion criteria: review articles, systematic reviews and meta-analyses, research protocols and study designs, conference abstracts without full text, studies conducted in institutional care, and studies without full text available.

C. Study selection process

The literature selection process is shown in the PRISMA diagram (Fig. 1). The initial search yielded 70 records. Before screening, we removed 11 review articles, leaving 59 records. During screening, we excluded 22 records that were not original research articles and 16 that did not meet the time frame. This left 21 articles eligible for assessment. Of these, we excluded 8 articles because their full texts were unavailable. We reviewed the remaining 13 articles in full and excluded 3 more sources (one protocol, one evaluation report, one research plan). Finally, 10 studies were included in the structured narrative review.

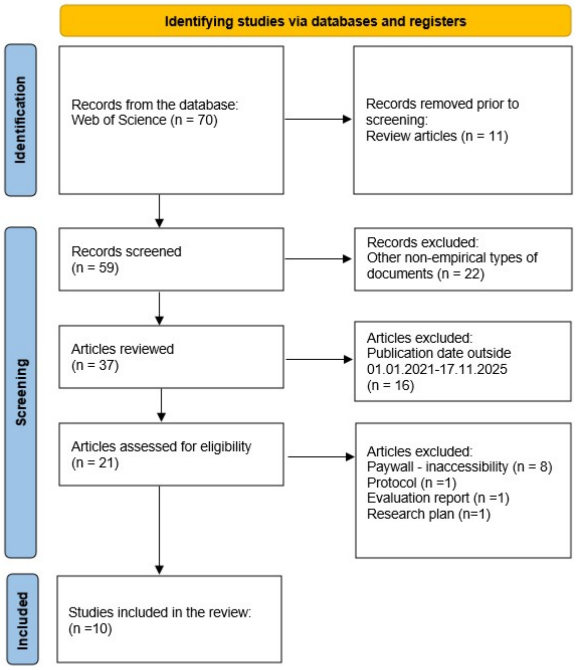

Fig. 1: PRISMA diagram

D. Quality assessment and data extraction

We assessed the methodological quality of the included studies descriptively, considering study design, sample size, presence of a control group, randomization, blinding of assessors, duration of follow-up, and completeness of data. We identified the main methodological limitations for each study. A detailed analysis is presented in the Discussion section.

We extracted data on authors, study design, sample characteristics, exposure description, control group, follow-up duration, measured outcomes, main findings, and reported limitations from the included studies. The extracted data are presented in Table 2 (Appendix 2) and described in the Findings section.

III. FINDINGS

A Robust Deep Feature Extraction Method for Human Activity Recognition [9]: The authors developed a model for human activity recognition (HAR) that converts 1D data from wearable sensors into spectral images (scalograms) via a continuous wavelet transform. The ResNet-101 model combined with the Morlet wavelet achieved the best performance, achieving 98.4% accuracy on the SisFall dataset and 98.1% on the PAMAP2 dataset, outperforming comparable state-of-the-art algorithms.

Impacts of Remote Physical Exercises on Functional Status [10]: A remote exercise intervention (via Zoom or booklets) in older adults at risk of disability during the COVID-19 pandemic did not result in statistically significant improvements in functional mobility (SPPB test) or frailty status compared with the control group. Nevertheless, participants in the intervention group reported higher levels of physical activity, but this did not translate into improved performance in daily activities.

The effectiveness and cost-effectiveness of assistive technology and telecare [11]: The large-scale randomized ATTILA study found that using assistive technology and telecare (ATT) in people with dementia did not prolong independent living at home or reduce the burden on caregivers compared with basic care. ATT was not cost-effective, and the intervention group reported lower quality of life after 104 weeks, as measured by the EQ-5D questionnaire.

Telehealth Lifestyle Pilot Study [12]: A pilot study of the HOPE program, based on occupational therapy and telehealth, found a statistically significant improvement in occupational performance among older adults in the community, as measured by the Goal Attainment Scale (GAS). Participants achieved or exceeded the expected level for 69.4% of their health goals, demonstrating the feasibility of brief virtual interventions to promote healthy lifestyles.

APP-Based Intervention for Depression in Spinal Cord Injury [13]: The use of a mobile application to support self-management significantly reduced depression in individuals with spinal cord injury living at home 24 weeks after hospital discharge, compared with the control group. The application enabled timely recognition of negative emotions and faster intervention by a multidisciplinary team, thereby preventing deterioration of mental health.

A Biologically Inspired Movement Recognition System [14]: The authors proposed a biologically inspired system for recognizing elderly people's movements using an asynchronous cellular automaton (ACAN) model within spiking neural networks (SNNs). Validated on FPGA hardware, the system achieved 83.3% accuracy on a new motion dataset and demonstrated suitability for energy-efficient, real-time applications.

Multimodal Approaches for Indoor Localisation [15]: The study presented two methodologies for indoor localization: one based on analyzing BLE signals during daily activities (accuracy 81.36%) and the other on analyzing behavioral patterns using an accelerometer and gyroscope (accuracy 81.13%). A comparison of machine learning methods showed that the Random Forest approach is the most accurate for determining spatial coordinates with the least error.

A Simplistic and Cost-Effective Design for an AAL System [16]: A conceptual system for simultaneous fall detection and indoor positioning was developed, combining smart cameras, wearable sensors, and proximity sensors. The system stands out for its cost-effectiveness and its integrated hardware and software design, enabling real-time multimodal data capture.

Effectiveness of a fitness-app prototype for home care service users [17]: Use of a customized fitness app on a tablet significantly increased the likelihood of regular physical activity and exercise frequency among home care users after four months. The effects were strongest among frequent app users and persisted through the 8-month trial, whereas the app had no effect on walking frequency at the group level.

AI-enabled multimodal monitoring for elderly and post-stroke patients [18]: In a 24-month study of elderly and post-stroke patients, an integrated artificial intelligence system for multimodal monitoring detected clinical deterioration 14.8 days earlier than usual care and halved the rate of falls. Despite higher initial costs, the system resulted in net financial savings due to reduced hospitalizations and emergency room visits and improved the quality of life of users.

IV. Synthesis of Evidence on the Effectiveness and Challenges of Assisted Living Technologies

The central part of the paper is devoted to a comprehensive synthesis of the findings from 10 selected empirical studies that shed light on various dimensions of the use of smart home technologies among older adults. To go beyond a mere technical description of the solutions, we link the findings within a multidisciplinary framework that combines technological accuracy, clinical outcomes, and the economic sustainability of systems [11], [18]. This approach allows us to identify the factors that have a key impact on the acceptance of technology and its long-term effectiveness in real-world environments [9], [17]. Below, these topics are broken down into technical aspects of performance, impact on independence and health, economic analysis, and key barriers to implementing solutions in practice.

A. Technical capabilities and accuracy of AAL systems

Reliable recognition of activities of daily living (ADL) is the technical foundation of ambient-assisted living systems, enabling objective monitoring of the user's condition without active involvement. Modern deep learning methods achieve exceptionally high reliability in motion identification. Research using advanced architectures such as ResNet-101, combined with spectral visualization of inertial data, shows that it is possible to achieve up to 98.4% accuracy in recognizing activities of daily living [9]. The significance of this method lies in the use of the continuous wavelet transform (CWT), which converts raw sensor data into spectral images, enabling AI models to visually recognize complex movement patterns without invasive cameras [9]. Such accuracy is crucial for reducing the number of false alarms, which could otherwise cause unnecessary stress for users and caregivers [9]. Using methods such as continuous wavelet transformation, modern systems successfully distinguish between normal movement and critical events, which was extremely difficult in the past due to noise in sensor data [9]. This allows the technology to adapt over time to each user's specific movement style, increasing its long-term utility and reducing the need for manual parameter adjustment [9]. The development of robust algorithms thus ensures safety without compromising privacy through invasive data collection methods.

Despite a growing emphasis on accuracy, the latest developments in gerontechnology are strongly focused on energy efficiency in wearable devices. Research into biomimetic algorithms, specifically spiking neural networks (SNNs), shows that it is possible to significantly reduce a device's energy consumption and thus extend its autonomy [14]. Although such models achieve slightly lower motion recognition accuracy (around 83.3%), their energy efficiency enables practical long-term use without frequent recharging. Discussion of these systems reveals the necessity of a trade-off; although such models achieve slightly lower accuracy, their energy efficiency reduces the burden of frequent recharging for older users, which is often more important in a real-world environment than absolute technical perfection [14]. This is crucial for the acceptance of technology among older people, who often forget to maintain their electronic devices [14].

In addition to activity recognition, accurate localisation within living spaces is essential for user safety, enabling rapid assistance in emergencies. Machine learning algorithms enable localisation in specific areas of a space with more than 81% accuracy, achieving a minimum horizontal error of less than 8 cm when determining coordinates [15]. At the same time, development is focused on increasing the affordability of these systems for end users. A proof-of-concept demonstrates that it is possible to establish a functional AAL environment for less than $300 using commercially available components [16]. Affordable hardware thus provides the necessary infrastructure for the wider implementation of smart home solutions [15], [16].

B. *Impact of digital interventions on clinical outcomes and independence*

Empirical evidence confirms that targeted digital interventions significantly improve the functional status and psychological well-being of older adults. Particularly noteworthy are advanced systems powered by artificial intelligence that combine wearable and environmental sensors to enable comprehensive monitoring of user safety [18]. Such systems not only reduce the rate of falls by up to 42% but also enable significantly faster detection of health deterioration [18]. Redundant information capture, such as simultaneous detection of a fall sound and a sudden interruption in movement, drastically reduces false alarms and increases user confidence in the system [18]. Rapid action based on this data directly prevents the long-term consequences of injury or illness.

In addition to safety considerations, ambient-assisted living technology actively promotes aging through digital platforms for physical exercise. Research shows that using dedicated apps and remote exercise guidance effectively maintains functional [10], [18]. Interventions targeting the so-called "pre-disability" phase are particularly valuable, as organized remote exercise can prevent or significantly delay the onset of more serious functional limitations [10]. Such preventive programs are not only cost-effective but also crucial for maintaining long-term quality of life and preventing social exclusion, which often accompanies a decline in physical abilities [10]. Users who regularly use fitness apps increase their physical activity by 28% and the frequency of their workouts by almost half [17]. These effects persist for up to 8 months after the introduction of the technology, confirming the sustained impact of digital tools [17]. Digital platforms not only offer structured exercise but also leverage social interaction and feedback mechanisms, which are key to long-term adherence to an active lifestyle [17].

Digital support affects not only physical but also mental health in older adults. Interventions based on self-care and tele-rehabilitation apps statistically significantly reduce depression in specific user groups [13]. Improvements in psychological well-being are directly linked to better achievement of personal goals of independence in the home environment. Digital solutions are thus proving to be an effective tool for comprehensive support of independent living, as they strengthen motivation and self-confidence in older adults [12].

C. *Economic efficiency and the gap between technological approaches*

The economic justification for AAL technologies is closely linked to their ability to prevent costly acute events in the healthcare system. Analysis of the available evidence reveals a significant gap in cost-effectiveness between different technology levels and populations. Advanced multimodal systems supported by artificial intelligence suggest the possibility of significant savings, up to $15,000 per case in preventing long-term hospitalisation or institutionalisation [18]. However, these estimates should be interpreted with caution, as they depend on the specifics of the healthcare system and the user's level of risk. These savings result from proactive monitoring, which reduces the incidence of falls and prevents costly hospitalisations and premature institutionalisation [18].

In contrast, basic assistance technologies (ATT), such as simple motion detectors, do not achieve the expected effectiveness in certain groups. Research in dementia care shows that using basic technology without adaptation does not prolong independent living [11]. The economic value of technology, therefore, depends not only on its price but also on its integration into a comprehensive care model that addresses specific needs [11]. Investment in technology must therefore be strategically planned in line with the user profile.

At the same time, advances in hardware are steadily lowering the cost of setting up a smart home. Using commercially available components, basic fall-detection systems can be built for less than $300 [16]. While affordability is an important step toward broader adoption, comprehensive sustainability requires a shift toward active, integrated systems. These systems directly reduce the need for institutional care, justifying the initial investment over the long term [18].

D. *Implementation challenges: Privacy, costs, and digital literacy*

Despite the proven advantages of AAL technologies, their successful implementation faces numerous challenges that extend beyond the technological framework. One of the most significant obstacles is protecting older users' privacy and personal data. Users express a strong preference for non-intrusive technologies that use "edge" data processing and transmit only anonymized information [9], [14], [18]. Privacy protection is thus becoming a key condition for trust and long-term use of these systems.

In addition to ethical issues, the success of technological interventions is limited by structural factors, such as the digital divide. The reliable deployment of smart home systems requires a stable broadband Internet connection, which is often unavailable in rural areas [18]. Older adults' low digital literacy is another obstacle, as the positive effects on independence are statistically significant only among regular and skilled users [17], [18]. Without systemic support for training, technology cannot reach its full potential.

Finally, the long-term sustainability of AAL systems depends on their interoperability and the presence of a supportive ecosystem. Closed systems limit flexibility, which is why open standards are needed to combine devices from different manufacturers [15], [16]. Fear of stigmatization remains another significant psychological barrier, as older adults often reject devices that are too visible and are labeled as helpless or sick by society. The development of invisible sensors integrated into furniture and the environment is therefore a priority for the gerontechnology industry, as it increases the likelihood that users will accept the technology as a natural part of their home [16]. Technology cannot completely replace human care, but it serves as a complementary part of it that requires technical support [10], [11]. Successful integration requires close cooperation among technologists, healthcare professionals, and users.

A review of the literature also reveals specific shortcomings in this area. A critical issue remains privacy in intimate spaces such as bathrooms and bedrooms, where the risk of falls is highest but user resistance to sensors is greatest [9], [18]. In addition, research is strongly biased, as studies often include "technologically literate" volunteers, thereby excluding the most vulnerable groups [17]. The ethical dilemma between ensuring safety through constant monitoring and preserving the autonomy of older adults thus remains a central challenge for future development [11], [18].

V. DISCUSSION

This review synthesized empirical evidence on the clinical and economic effectiveness of smart home and ambient-assisted living (AAL) technologies designed to support independent living among older adults. Across the included studies, a clear theme emerges: technical capability is advancing rapidly, yet translating this into consistent, patient- and system-relevant outcomes is constrained by socio-technical factors (privacy, usability, integration into care pathways) and by the limited availability of robust, long-term evaluations. AAL systems increasingly demonstrate strong performance in activity recognition and related sensing tasks that underpin safety monitoring and contextual assistance. In particular, accurate recognition of activities of daily living (ADL) is repeatedly identified as a core prerequisite for risk detection (e.g., falls, inactivity patterns) and timely intervention, especially when systems aim to operate unobtrusively and continuously [9]. At the same time, the literature indicates that higher algorithmic accuracy does not automatically yield real-world effectiveness unless systems are engineered for reliability under everyday conditions, including variable user behavior, inconsistent device use, and home-environment noise. A practical constraint highlighted in the evidence is that solutions that rely on frequent device interaction, charging, or calibration can underperform in the very populations they target. Even when recognition accuracy is high, sustained utility may be undermined when older users forget or cannot maintain electronic devices, a particular concern for wearables and hybrid systems that require active engagement [14]. This supports the broader design implication that maintenance overhead must be minimized and that adaptive error handling and passive sensing should be prioritized where feasible. Preventive and rehabilitation-oriented digital supports also show potential, particularly in strengthening adherence and sustaining engagement with physical activity. Remote exercise interventions demonstrate clinically relevant effects on physical function and related outcomes, although impacts on everyday activity, such as walking frequency, may not consistently appear at the group level, emphasising heterogeneity in response and context [10]. Importantly, these interventions can influence independence indirectly by improving capacity, confidence, and routine formation, which are key determinants of long-term function and fall risk [17]. Collectively, the findings suggest that AAL is most effective when embedded in behavioural and rehabilitative logic, rather than treated as a purely technical monitoring solution.

Several studies reinforce that AAL effectiveness depends on more than physical safety and functional metrics. Digital supports may influence mood, perceived autonomy, and motivation, which, in turn, shape engagement, adherence, and persistence with healthy behaviors. App-based mental health interventions demonstrate measurable effects and underscore the importance of psychosocial outcomes in technology-supported independent living [13]. Similarly, telehealth approaches that incorporate lifestyle guidance or occupational-therapy–relevant supports can strengthen motivation and self-confidence, especially when interventions are personalized and feasible for routine use [12]. In practical terms, this means AAL evaluations should treat mental health and social participation as core mediators of effectiveness, not optional secondary endpoints.

The economic case for AAL is often framed around avoiding costly events (hospitalizations, emergency visits) and delaying institutionalization. Evidence supporting this logic is strongest where systems demonstrably reduce acute utilization and improve quality of life in high-risk cohorts [18]. Nevertheless, cost-effectiveness is not inherent to “having technology”: it depends on who receives it, what service model surrounds it, and how benefits accrue over time.

A key finding is that basic assistive technologies and telecare packages may fail to be cost-effective within typical evaluation horizons, particularly when installation, monitoring, and response costs are high relative to measured quality-of-life gains [11]. This does not imply that such technologies are ineffective, but rather that value is sensitive to implementation context and may require longer follow-up to capture downstream effects. In contrast, the literature suggests that decreasing hardware costs and more efficient software architectures (including simplified designs) can improve affordability and scalability, particularly when solutions reduce the need for extensive manual parameterization and maintenance [16], [18]. The discussion implication is that procurement and scaling should be guided by risk stratification and budget-impact logic, matching system intensity to user profile and expected avoidable costs.

VI. GAPS AND FUTURE DIRECTIONS OF RESEARCH

The reviewed evidence also reveals specific gaps that should shape the next phase of research and development. First, there remains an unresolved tension between safety monitoring and privacy, especially in high-risk locations (e.g., bathrooms and bedrooms) where sensing is most useful but also most sensitive [9], [17]. Second, while accuracy and technical feasibility are improving, more studies are needed that evaluate AAL as a socio-technical intervention—technology plus service model—using robust comparators and longer horizons to test claims of reduced institutionalization and healthcare utilization [11], [18]. Third, the field would benefit from convergence on a core outcome set that consistently captures independence-relevant endpoints, caregiver burden, mental health, and utilization, enabling more comparable evidence generation across heterogeneous systems.

VII. CONCLUSION

The literature review confirms that the field of ambient assisted living (AAL) technologies is at a turning point, as technology moves from being merely a passive tool to becoming a proactive guardian of independence. The main finding of the analysis is that the success of a smart home lies not in its complexity but in its ability to blend seamlessly into the daily life of an older person. The proven 42% reduction in falls and significant economic savings are not merely statistics; they are proof that properly implemented artificial intelligence can prolong dignified living at home while reducing the burden on public finances.

Despite optimistic results, the path to widespread use remains fraught with obstacles, requiring greater interoperability among hardware providers in the coming years so that systems do not remain isolated islands accessible only to technologically literate individuals. It will also be necessary to develop clearer protocols for edge computing to ensure security in the most intimate spaces without making users feel monitored. Future research must include those who are currently digitally excluded and develop solutions tailored to specific cognitive declines where current basic systems fail.

If we dare to dream about the future in a decade or two, the smart home will no longer be a collection of wall-mounted sensors but an intelligent, empathetic ecosystem. We can imagine an environment that is completely invisible – where smart textile fibers in carpets detect heartbeats and furniture subtly adapts to the user's movements. Future technology will not only prevent falls but also actively recognize signs of loneliness or early symptoms of illness before they manifest physically.

The goal is not to replace human contact but to enable it. Technology must become the silent partner that removes the elderly person's fear of helplessness and offers society a sustainable model of care, where old age no longer means institutionalization but a new, safe, and technologically supported chapter in life. By overcoming the digital divide, we will transform homes into spaces where technology serves people without compromising their dignity or privacy.

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