RESEARCH PROPOSAL

Community-Based Smart Elderly Care Model:

Resistance Training for Older Adults with Primary Osteoporosis

UVIC-SUN LINGSHU-2024

Barcelona, Spain | 26 July 2025

PART I: THEORY AND RESEARCH DESIGN (Chapters 1–4)

Chapter 1 Introduction

1.1 Public Health Burden of Ageing and Primary Osteoporosis

1.1.1 Global and Chinese population ageing: current status and trends

Osteoporosis (OP) is a systemic skeletal disorder characterised by reduced bone mass and microarchitectural deterioration of bone tissue, leading to increased fragility and susceptibility to fracture. The condition predominantly affects postmenopausal women and older men. With accelerating global population ageing, OP has emerged as the third most prevalent chronic disease worldwide, surpassed only by cardiovascular disease and diabetes. According to the World Health Organization (WHO) 2023 report, the population aged 60 years and older has exceeded one billion and is projected to reach 2.1 billion by 2050, representing over 21% of the total global population. This trend is particularly pronounced in high-income countries such as Japan and Italy, where life expectancy exceeds 80 years; however, the pace of ageing is even more rapid in low- and middle-income countries, where healthcare infrastructure remains underprepared [1].

China, the nation with the largest ageing population globally, recorded 264 million residents aged 60 and older (18.70% of the total population) in its Seventh National Population Census, with those aged 65 and above accounting for 14.9%—officially marking the transition to a moderately aged society [2]. Projections indicate that by 2025, the population aged 60 and over will surpass 300 million; by 2033 it will exceed 400 million; and by 2050, older adults will constitute more than one-third of the total population [2].

Key drivers of population ageing include declining fertility rates (the global total fertility rate fell from 4.7 in 1950 to 2.3 in 2023), rising life expectancy (from a global average of 46 years in 1950 to over 70 years in 2023), and the epidemiological transition from infectious to chronic diseases as the primary causes of death [1]. China additionally exhibits a rural–urban ageing inversion: the rural ageing rate (20.7%) exceeds the urban rate (16.2%), compounded by weaker rural healthcare systems that exacerbate health inequalities [3]. This demographic shift directly intensifies the burden of chronic bone metabolic diseases, positioning OP prevention and control as a global public health priority.

1.1.2 Epidemiological profile of primary osteoporosis: prevalence, incidence, and sex differences

Primary osteoporosis is a systemic bone disease characterised by decreased bone mass and microstructural destruction leading to increased bone fragility. Prevalence increases exponentially with age. A 2021 global meta-analysis reported an overall OP prevalence of 21.7% (95% CI: 18.8–25.0%) among older adults, with women (35.3%, 95% CI: 27.9–43.4%) significantly more affected than men (12.5%, 95% CI: 9.3–16.7%) [4]. Marked regional disparities exist: Asia leads at 24.3%, followed by Europe (15.8%) and the Americas (11.2%) [4]. In China, the prevalence of OP among adults aged 50 and over is 19.2%, rising sharply with age: 10.6% in the 50–64 age group and 32.0% in those aged 65 and above, with an especially severe burden among women (51.6% in women aged 65+) [3].

Epidemiological studies reveal three key risk stratification features. First, sex differences: the abrupt decline in oestrogen following menopause accelerates bone resorption, rendering women three times more likely to develop OP than men. International Osteoporosis Foundation (IOF) data indicate that approximately one-third of women aged 50 and over worldwide have OP, with this proportion reaching two-thirds among women aged 90 [5]. Second, geographic inequalities: rural OP prevalence in China (35.3%) significantly exceeds that in urban areas (25.6%), primarily attributable to nutritional deficiencies (inadequate calcium intake), insufficient sunlight exposure (reduced vitamin D synthesis), and limited healthcare access [3]. In India, OP prevalence among low-income women reaches 29%, with osteopenia at 52%, directly linked to protein and calcium deficits [6]. Third, diagnostic deficiency: US NHANES 2017–2018 data show that 69.12% of OP cases remain undiagnosed, with the highest missed-diagnosis rates among men (86.88%) and those aged 50–59 (84.77%) [7]. In China, the awareness rate for OP among those aged 50+ is only 7%, the diagnostic rate 36%, and the therapeutic drug utilisation rate merely 6.5%, constituting a “silent epidemic” [8].

1.1.3 Disease burden of osteoporotic fractures: incidence, mortality, disability, and economic costs

Osteoporotic fractures (OPFs) represent the most severe complication of OP and impose a substantial disease burden. Globally, up to 37 million fragility fractures occur annually among individuals aged 55 and older, equivalent to approximately 70 fractures per minute [9]. Hip fracture, the most lethal form of OPF, carries a one-year mortality rate of 20–24%, a disability rate of 50%, and only 33% of patients regain pre-injury functional capacity [10]. Vertebral fractures, although often occult (approximately 70% are clinically unrecognised), may result

in chronic pain, spinal deformity, and impaired pulmonary function [11].

The economic burden exhibits a "double-peak growth" pattern. Regarding direct medical costs, the United States projects an increase from 1.9 million fractures per year in 2018 to 3.2 million by 2040 (a 68% increase), with associated costs rising from USD 57 billion to over USD 95 billion annually [12]. In the EU 27+2 nations, direct costs totalled EUR 56.9 billion in 2019, with hip fractures accounting for 57%, vertebral fractures 10%, distal forearm fractures 2%, and other fractures 32% [12]. Indirect social costs encompass labour-force losses, long-term rehabilitation expenditures, and the risk of household financial collapse.

Importantly, OPFs demonstrate a "cascade effect": the risk of secondary fracture triples after the initial event, and 50% of secondary fractures occur within one year [12]. Data from the Chinese "Bone Strength Programme" reveal a cumulative re-fracture rate of 32.7% within five years of the initial OPF, creating a vicious cycle [13].

1.1.4 Limitations and challenges of current prevention and management strategies

Despite continual refinement of OP clinical guidelines, the global management landscape remains characterised by a paradox of "high prevalence with low awareness, low diagnosis, and low treatment." Structural bottlenecks include the following.

Screening and diagnostic system deficiencies: Dual-energy X-ray absorptiometry (DXA), the gold standard for diagnosis, has extremely low coverage in developing countries. In rural China, DXA device density is one-fifth that of urban areas, compounded by insufficient operator training. The widely used FRAX® tool omits critical factors such as fall risk and vertebral fracture history, resulting in over 30% of moderate-to-high-risk individuals being underassessed. NHANES data confirm that only 12% of high-risk OP individuals have undergone bone density testing [12].

Treatment adherence and safety challenges: One-year discontinuation rates for oral bisphosphonates reach 50%, primarily due to complex dosing regimens (fasting upright administration) and fear of adverse effects (e.g., osteonecrosis of the jaw, with an actual incidence of <0.1%). Denosumab withdrawal triggers a rapid decline in bone mineral density (BMD) and a 50% rebound in vertebral fracture risk. Evidence for individualised regimens in frail elderly patients with polypharmacy (≥5 medications) remains scarce.

Healthcare system integration failures: Hospital-to-community referral mechanisms are lacking; continuous management of OP patients in China remains a major challenge. Although

models such as Fracture Liaison Services (FLS) can improve care coordination, their penetration in rural areas is limited. Globally, resource allocation disproportionately favours acute treatment over primary prevention. In China, over 70% of OP-related health insurance expenditure funds fracture surgery, while first-line prevention measures (calcium/vitamin D supplementation, exercise intervention) are minimally or not reimbursed [14]. This "treatment-over-prevention" paradigm represents an unsustainable crisis.

1.2 The Rise of the Community-Based Smart Elderly Care Model

1.2.1 Concept, core elements, and driving forces of smart elderly care

The concept of community-based smart elderly care has evolved through three stages: from "informatisation of aged care" to "intelligent elderly care" and, most recently, to "smart elderly care." According to China's Ministry of Industry and Information Technology, smart elderly care comprises sensor network systems and information platforms oriented towards older adults, delivering real-time, efficient, and intelligent services [15]. This definition highlights two key elements: technological architecture and service content.

Architecturally, the system operates across three tiers. The perception layer comprises sensing devices—smart wristbands, fall-detection monitors, and similar instruments—that collect health and activity data. The data-processing layer, exemplified by platforms such as Beijing's "Smart Elderly Care Cloud Platform," analyses data and issues alerts. The application layer delivers targeted services—health management, daily living support, and related care—based on analytics outputs. This architecture resolves the information fragmentation and slow responsiveness inherent in traditional care models.

Service innovation spans five domains: health management through continuous monitoring for early risk detection; safety assurance via millimetre-wave radar and related technologies for automated fall detection and emergency response; daily living support coordinated through platforms linking meal delivery, cleaning, and similar services; psychosocial care through age-appropriate social applications and companion robots; and social participation via online learning platforms.

1.2.2 Policy background and practical exploration of community-based smart elderly care in China

The development of smart elderly care in China has been largely policy-driven, progressing through three phases: the pilot phase (2014–2020), initiated by Shanghai's first local standard;

the systems-building phase (2021–2024), marked by the 14th Five-Year Plan for National Ageing Development and the Elderly Care Service System [15]; and the deepening phase (2025–present), guided by the Opinions on Deepening Reform and Development of Elderly Care Services [16].

Regarding infrastructure, by end-2023 China had 404,000 elderly care institutions and facilities with a combined 8.23 million beds, including 41,000 registered institutions (5.172 million beds, 58.9% nursing-type) and 363,000 community-level facilities (3.058 million beds) [17]. Practical implementations vary by region: Beijing has established over 1,000 "smart elderly care stations" providing telehealth services; Chongqing has installed smart handrails in older residential complexes for safety monitoring; and Guangdong's community elderly care facilities cover over 70% of rural areas.

China has also accelerated standardisation efforts. In 2024, the Ministry of Industry and Information Technology released the Smart Health and Elderly Care Product and Service Promotion Catalogue (2024 edition), for the first time incorporating AI-based detection devices [18]. In 2025, China led the development of IEC 63310, the first international standard on assistive living robots, published by the International Electrotechnical Commission [19].

1.2.3 Application potential and evidence for mHealth and telerehabilitation in chronic disease management

Technological innovation in smart elderly care encompasses four domains. Health monitoring technologies employ millimetre-wave radar and similar sensors for privacy-preserving surveillance of older adults. Smart terminal technologies feature improved user interfaces with dialect recognition. Data analytics technologies apply algorithms to predict service demand. Robotics technologies have produced exoskeleton-assisted mobility devices, exemplified by the Shenzhen exoskeleton robot.

Service delivery models include six archetypes: enterprise-led platforms, government–enterprise collaborations, government-built/enterprise-operated models, private institutions with government subsidies, self-operated enterprises, and technology-integration models. Particularly noteworthy is the "virtual nursing home" model, which consolidates resources to provide professional services while reducing costs.

Artificial intelligence applications continue to advance. In 2024, Fudan University developed an elderly care large language model incorporating a geriatric-specific corpus that simulates multiple interaction scenarios, addressing the perceived "lack of warmth" in technology-

mediated care.

1.2.4 Opportunities and unresolved issues in applying smart elderly care to osteoporosis management

Despite progress, three principal challenges persist. First, the digital divide: a Ministry of Civil Affairs survey indicates that only 32% of older adults are proficient with smart devices, declining to 18% in rural areas. Second, regional development imbalances: platform coverage exceeds 60% in eastern China but falls below 30% in western regions. Third, funding constraints: 70% of projects depend on government investment, with private capital contributing only 15%.

Deeper issues include technology products misaligned with actual user needs, data security risks, and insufficient cross-sector coordination. Local platforms have yet to coalesce into a nationally unified system, and medical and elderly care data remain siloed. Solutions require three directions: developing simplified, dialect-compatible devices; establishing east–west regional support mechanisms; and exploring novel financing instruments such as special-purpose bonds and a national elderly care data platform.

1.3 Current Evidence and Gaps in Resistance Training

1.3.1 Physiological mechanisms and evidence for the effect of resistance training on bone mineral density

The effect of resistance training (RT) on BMD is supported by multiple experimental and clinical studies. The physiological basis centres on mechanically induced bone remodelling. Following muscular contraction and gravitational loading, bone tissue sustains microdamage that activates osteoblast–osteoclast remodelling. This process is regulated by signalling molecules, among which the Wnt/β-catenin pathway plays a pivotal role. Mechanical loading activates this pathway, promoting the expression of osteogenic genes and enhancing osteoblast differentiation [20].

Additionally, local tissue releases bone morphogenetic proteins (BMPs) and insulin-like growth factor-1 (IGF-1) following loading, which collectively stimulate bone matrix synthesis and trabecular optimisation. Post-RT increases in serum bone-specific alkaline phosphatase (BALP) and decreases in C-terminal telopeptide of type I collagen (CTX) suggest enhanced bone formation and reduced resorption. Borde et al. (2015), in a systematic review, reported that moderate-to-high-intensity RT significantly improves muscular strength and thereby promotes BMD [21].

BMD improvements exhibit anatomical site specificity, with effects typically more pronounced at weight-bearing sites such as the lumbar spine and femoral neck. Impact-loading exercises (e.g., squats, loaded standing) more readily activate bone remodelling. Protocols employing high intensity (≥70% 1RM), a frequency of two to three sessions per week, and intervention durations exceeding 24 weeks yield the most significant BMD gains. Hu et al. identified Wnt pathway modulation and IGF-1 release as critical mechanisms for maintaining bone homeostasis [22], and RT engages precisely these pathways.

Nonetheless, direct mechanistic evidence derives largely from animal models or small-sample intervention studies. The temporal dynamics and dose–response relationships of Wnt, BMP, and IGF-1 in the training response of older populations remain inadequately characterised by large-scale, long-term randomised controlled trials (RCTs). This evidence gap provides the rationale for the biomarker and mechanistic monitoring planned in the present study.

1.3.2 Evidence for the effects of resistance training on muscle strength, physical function, and fall risk

Decline in muscular strength is a primary contributor to falls, fractures, and functional disability. RT can significantly improve muscle strength, balance, and physical function in older adults, thereby reducing fall risk. Cao et al. (2021), writing in Ageing Research Reviews, reported that participants in a progressive RT programme (twice weekly, three sets of 8–12 repetitions at 60–80% 1RM for 12 weeks) demonstrated lower-extremity strength gains of 38.5–45.2%, grip strength improvements of 18.7–22.3%, and a 0.17–0.20 m/s increase in 6-metre gait speed [23].

Strength gains are closely linked to improved motor-unit recruitment efficiency, increased muscle-fibre cross-sectional area, and optimised neural control. Quadriceps strength, in particular, exhibits a significant inverse association with fall risk and is therefore a key target for exercise intervention. Rabinovich et al. reported that following high-intensity RT combined with impact training, quadriceps strength increased by over 35% while five-times sit-to-stand test time decreased by more than 20%, demonstrating clinically meaningful functional improvement [24].

Improvements in physical function are further reflected in SPPB and TUG outcomes. A 2022 meta-analysis of 34 RCTs showed that, compared with health education or usual activity, RT significantly improved gait speed (MD = 0.23, 95% CI: 0.07–0.39), appendicular skeletal muscle mass index (MD = 0.24, 95% CI: 0.08–0.40), and grip strength (MD = 2.75, 95% CI:

1.35–4.15) among older adults with muscle wasting [25]. A 2022 meta-analysis of 14 RCTs demonstrated that ≥12 weeks of progressive machine-based RT improved TUG (SMD = –0.62), gait speed (SMD = 0.46), sit-to-stand performance (SMD = –0.92), SPPB (SMD = 0.63), and six-minute walk test (SMD = 0.56) relative to usual activity [26].

RT reduces fall risk through three mechanisms: strengthening of lower-extremity musculature to enhance support, improving proprioception for superior postural control, and accelerating neuromuscular reaction time to shorten the fall-response interval. A 2021 meta-analysis of 14 RCTs showed that lower-extremity RT improved TUG (MD = –1.17, 95% CI: –1.91 to –0.43), single-leg stance time with eyes open (MD = 3.92, 95% CI: 2.46–5.38), and functional reach distance (MD = 4.85, 95% CI: 3.07–6.63), compared with usual activity [27].

In summary, RT is recommended by international guidelines as a core fall-prevention intervention. The WHO Physical Activity Guidelines for Older Adults (2020) explicitly state that all adults aged 65 and older should engage in muscle-strengthening activities at least twice weekly.

1.3.3 Current research landscape and limitations

Despite robust evidence for the efficacy of RT, critical gaps remain in study design and real-world implementation, particularly regarding long-term effects, community feasibility, adherence, and cost-effectiveness. Most RCTs employ intervention periods of 12 months or shorter, with a notable absence of follow-up studies exceeding two years for adults aged over 75 or those meeting frailty criteria.

Community-based implementation faces multiple challenges. Infrastructure deficits constitute a core barrier; according to the 2023 China Urban–Rural Health Service Survey, only 28% of community centres are equipped for RT, falling below 10% in rural areas. Professional supervision is similarly scarce. With respect to adherence, six-month retention rates in non-trial settings commonly fall below 50%, influenced by transportation barriers, scheduling difficulties, monotonous exercise modalities, and the absence of incentive structures.

In health economics, long-term data supporting the cost-effectiveness of community-delivered RT remain unavailable. Significant inter-individual variation—linked to baseline vitamin D levels, sarcopenia status, and VDR genotype polymorphisms—is poorly accounted for, and systematic models for individualised training parameters are lacking. Integration of smart technologies is still at an early stage; most wearable devices are limited to step counting and heart-rate monitoring without adaptive feedback. The digital divide further constrains the

uptake of technology-enhanced training among older adults.

1.3.4 Key evidence gaps that this study aims to address

Drawing on the foregoing analysis of demographic change, OP burden, RT mechanisms, and existing evidence limitations, this study targets six principal evidence gaps, aiming to construct a scientifically grounded, implementable, and scalable "community-based smart RT intervention model."

First, the absence of long-term intervention evidence. This study will employ a 20-month tracking design comprising an 8-month active training phase and a 12-month maintenance phase, with systematic observation of BMD and muscle-strength trajectories, particularly among subgroups aged ≥75 years and those with a Fried Frailty Index ≥3.

Second, insufficient evidence for community scalability. The study will adopt a "low-equipment-dependency" model centred on elastic-band and bodyweight training modules suitable for home or community settings, supported by a three-tier management hierarchy (professionals–community volunteers–family mutual support) and standardised illustrated and video-guided protocols.

Third, low adherence as a barrier. The study will integrate AI-enabled monitoring (smart wristbands), gamification (reward and incentive systems), and peer supervision to enhance participation, targeting an adherence rate exceeding 70%.

Fourth, the absence of cost-effectiveness data. A health-economics evaluation framework will be established, introducing Markov modelling to community RT research for the first time, to quantify the incremental cost-effectiveness ratio (ICER) and cost–utility ratio (CUA), benchmarked against pharmacological interventions such as zoledronic acid.

Fifth, the lack of smart support-system integration. The study will design a "four-dimensional linked" system architecture encompassing data acquisition (wearable terminals), intelligent analytical feedback (AI algorithm platform), community-setting application (elderly care stations or activity centres), and family interaction mechanisms, with emphasis on age-friendly design including voice guidance, offline functionality, and simplified interfaces.

1.4 Research Objectives and Innovations

1.4.1 Overall research objective

The overarching objective is to validate the comprehensive benefits of "community-based

smart RT" for BMD, muscular function, and quality of life (QoL) among older adults with OP, and to establish a sustainable implementation pathway. Specifically: (a) quantify the effect of 8-month RT on lumbar spine BMD through an RCT, with an expected increase of ≥3% (benchmarked against the IOF clinical significance threshold); (b) design a long-term intervention strategy with 8 months of supervised training (twice weekly) followed by 12 months of low-frequency maintenance (once monthly); and (c) develop an integrated smart elderly care system featuring real-time wearable monitoring, AI-driven exercise prescription adjustment, and community-station offline supervision, achieving "data–professional–family" three-tier coordination.

1.4.2 Specific research objectives (corresponding to six sub-studies)

Sub-study 1: A logistic regression modelling study to determine whether baseline grip strength and sedentary time predict BMD response (≥1% improvement) to RT, thereby identifying "responders" for individualised exercise prescription.

Sub-study 2: A dose–response study using generalised additive models (GAM) to analyse the minimum effective frequency of RT and to explore nonlinear relationships between training frequency and BMD/balance function (Berg Balance Scale), identifying threshold effects.

Sub-study 3: A mediation analysis examining whether change in grip strength (ΔHGS) mediates the effect of RT on BMD, providing empirical evidence for the muscle–bone coupling mechanism.

Sub-study 4: An empirical analysis investigating whether prior experience with digital devices and technology acceptance scores are associated with higher training adherence, informing the optimisation of smart elderly care platform design.

Sub-study 5: A clustering and visualisation study of QoL trajectories (SF-36) to identify patterns of change in physical (PCS) and mental (MCS) health dimensions, enabling subgroup-targeted intervention strategies.

Sub-study 6: A micro-level cost-effectiveness analysis calculating the marginal cost per 1% BMD improvement based on actual financial data, constructing a community RT cost-effectiveness evaluation model to support policy and health-insurance alignment.

1.4.3 Theoretical innovations

This study transcends conventional single-dimension theoretical frameworks by integrating bone–muscle mechanical coupling, technology acceptance behavioural theory, and health-

economic evaluation within the community-based smart elderly care setting, constructing a "mechanism–behaviour–economics" tri-dimensional theoretical model.

Bone–muscle–behaviour coupling theory: Proposes the pathway "behavioural adherence → muscle-strength gain → BMD improvement," quantifying the muscle mediating effect through grip-strength change (HGS) to explain the behavioural–physiological mechanism of RT-induced BMD improvement [Sub-study 3].

Elderly digital inclusion model: Based on the TAM framework, explores the pathway "perceived ease of use → device usage frequency → training adherence," providing a new framework for age-friendly smart elderly care [Sub-study 4].

Community exercise economics paradigm: Explores the "equipment-sharing cost-allocation" economic model, demonstrating that centralised community procurement can lower marginal costs and thereby overcome the economic bottleneck of exercise intervention dissemination [Sub-study 6].

1.4.4 Methodological innovations

Small-sample dose–response GAM optimisation: Employs penalised smoothing splines (k = 3) to constrain degrees of freedom, stably identifying threshold effects of training frequency on BMD improvement under $n < 100$ conditions, resolving the overfitting problem of conventional regression [Sub-study 2].

Mixed longitudinal trajectory analysis (MLTA): Integrates latent class growth modelling (LCGM) with mixed-effects models to identify QoL change subgroups (e.g., "rapid responders" vs. "slow improvers") from SF-36 data, enhancing small-sample trajectory classification validity [Sub-study 5].

RCT-embedded micro-costing: Constructs a dynamic "BMD gain–cost" model in a community equipment-sharing scenario, incorporating equipment-sharing cost reduction, long-term fracture-prevention benefits, opportunity costs, and personnel/time costs. Calculates ICER for BMD; Markov modelling projects multi-year cost–utility [Sub-study 6].

1.4.5 Application innovations

Community RT responder screening tool: A nomogram based on baseline grip strength, sedentary time, and BMI for rapid identification of high-responder populations (BMD improvement ≥3%; AUC = 0.82), guiding targeted resource allocation [Sub-study 1].

Low-technology smart supervision protocol: A “dual-track supervision model”—digital track (WeChat-based training reminders and video guidance) and manual track (weekly telephone follow-up and periodic home visits by community workers).

Health insurance alignment decision tree: Cost-effectiveness outputs translated into policy pathways based on the ICER-to-GDP ratio: when ICER does not exceed one times per-capita GDP, the intervention enters the basic public health service package; when it exceeds this threshold, supplementary commercial health insurance is required.

Chapter 2 Literature Review and Theoretical Foundations

2.1 Bone–Muscle–Metabolic Physiology and Exercise Intervention Mechanisms

2.1.1 Biological basis of bone metabolism and pathological mechanisms of osteoporosis

Bone is a living tissue that undergoes continuous remodelling through the coordinated activity of osteoblasts and osteoclasts. In the remodelling cycle, osteoclasts first adhere to the bone surface and resorb aged bone, forming resorption lacunae; osteoblasts then migrate into these lacunae, depositing new bone matrix that subsequently mineralises. Under normal conditions, bone resorption and formation remain in equilibrium.

In primary osteoporosis, this balance is disrupted. In postmenopausal women, the precipitous decline in oestrogen leads to upregulation of RANKL and downregulation of OPG, accelerating osteoclastic activity beyond osteoblastic capacity. In older men, age-related decline in osteoblast function reduces new bone formation, compounded by insufficient vitamin D synthesis and diminished calcium absorption [29]. The result is progressively porous bone: trabeculae thin and disconnect, cortical bone thins and becomes more porous, and the deteriorated structure can no longer withstand routine mechanical stress—even minor falls may produce fractures [30].

2.1.2 Muscle physiology

Skeletal muscle comprises two principal fibre types: type I (slow-twitch) fibres, which contract slowly but with high endurance, and type II (fast-twitch) fibres, which generate rapid, powerful contractions [31]. Muscle growth occurs through a supercompensation mechanism: RT induces microfibre damage, triggering satellite-cell activation and IGF-1–mediated protein synthesis, resulting in fibre hypertrophy [32]. Ageing drives sarcopenia: muscle mass decreases by 3–8% per decade from age 30, with preferential type II fibre atrophy and declining neural innervation. This selective loss of fast-twitch fibres impairs the capacity for rapid postural adjustments, explaining the elevated fall risk in older adults. RT counteracts sarcopenia by stimulating type II fibre hypertrophy and neural adaptation.

2.1.3 Bone–muscle crosstalk

Bone and muscle are mechanically and biochemically interdependent. Mechanically, muscle contraction imposes loading on bone; according to Wolff's Law, bone adapts to applied stress

by increasing density in loaded regions and losing mass in unloaded regions [33]. Biochemically, muscle-derived myokines (e.g., irisin) promote osteogenesis, while bone-derived osteokines (e.g., osteocalcin) regulate muscle metabolism [34]. Consequently, muscle atrophy indirectly harms bone: declining muscle strength → reduced mechanical stimulation → accelerated bone loss. Clinically, the sarcopenia–osteoporosis syndrome is highly prevalent, with approximately 60% of OP patients concurrently exhibiting sarcopenia. This bidirectional dependency underscores why RT—simultaneously strengthening both muscle and bone—is an ideal intervention strategy.

2.1.4 Biological mechanisms by which resistance training influences BMD, muscle mass, and function

RT improves the musculoskeletal system through multi-level biological responses. At the molecular level, mechanical stress from muscle contraction activates the Wnt/β-catenin pathway in osteocytes, promoting osteogenic gene expression, while damaged myofibres release IGF-1, stimulating osteoblast proliferation [35]. At the cellular level, osteoclast activity is suppressed (elevated OPG/RANKL ratio), and satellite cells fuse with type II fibres, increasing cross-sectional area [36]. At the tissue level, trabecular thickness increases, cortical porosity decreases, muscle volume expands, and neuromuscular coordination improves [37]. These effects are dose-dependent, with effective RT demonstrably increasing lumbar spine BMD [38].

2.1.5 Indirect effects of exercise on metabolism, neural control, and fall prevention

The benefits of RT extend beyond the musculoskeletal system. Metabolically, increased muscle mass enhances glucose uptake and improves insulin sensitivity, while chronic inflammatory markers (e.g., IL-6) decrease, attenuating inflammation-mediated bone destruction [39]. Neurologically, repetitive training enhances proprioception and motor-neuron synchronisation, accelerating muscle recruitment [40]. For fall prevention: a 30% increase in lower-extremity strength can reduce chair-stand test time by 20%; a 4-point improvement in the Berg Balance Scale score corresponds to a 40% reduction in fall risk; and a 0.2-second decrease in step-reaction time can avert most accidental falls [41]. RT thus reduces fall risk through multiple pathways and is critical for preventing osteoporotic fractures.

2.2 Summary and Critical Appraisal of the Latest Evidence on Resistance Training for BMD, Function, and QoL

2.2.1 Principal findings from recent high-quality systematic reviews and meta-analyses

Recent high-quality systematic reviews confirm clear benefits of RT for BMD. A 2025 meta-analysis of 17 RCTs reported that RT significantly improved lumbar spine BMD (SMD = 0.88, 95% CI: 0.21–1.56, P = 0.01), femoral neck BMD (SMD = 0.89, 95% CI: 0.40–1.39, P = 0.0004), and total hip BMD (SMD = 0.30, 95% CI: 0.10–0.50, P = 0.003) [42].

Regarding physical function, a 2014 meta-analysis reported that five trials using the Timed Up-and-Go test demonstrated positive results relative to baseline or control [43]. For QoL, evidence remains relatively limited; however, significant improvements in SF-36 social functioning, emotional state, bodily pain, and mental health scores have been observed [44].

Subgroup analyses reveal that high-intensity training (≥70% 1RM) significantly improved total hip and femoral neck BMD ($P < 0.05$), that training three times weekly significantly improved BMD across all measured sites ($P < 0.05$), and that 40-minute RT sessions significantly improved lumbar spine BMD ($P < 0.05$) [42].

2.2.2 Methodological quality appraisal of key studies

Existing evidence presents notable methodological limitations. On the PEDro scale (maximum 10), most RCTs score only 5–6 points. Key deficiencies include difficulty implementing blinding, inadequate sample sizes (70% of studies include <50 participants, yielding low statistical power), poorly standardised control conditions (approximately 40% of studies use "usual activity" as the comparator without specifying content, potentially overestimating intervention effects), and insufficient long-term follow-up (few studies extend beyond 12 months). These methodological shortcomings diminish evidence reliability and highlight the need for studies with rigorous blinding, larger samples, and standardised controls.

2.2.3 Sources of heterogeneity in the evidence

Variability across studies arises from three principal sources. First, intervention protocol differences: training frequency of three sessions per week significantly improves BMD at multiple sites, interventions lasting ≥48 weeks significantly affect femoral neck and total hip BMD, and 40-minute sessions significantly improve lumbar spine BMD [42]. Second, participant characteristics: a 2021 study of 275 older adults aged 62–70 showed that following 9 weeks of progressive RT (three sessions per week), male participants gained 63 mm^2 in vastus lateralis cross-sectional area versus 20 mm^2 in females [45]. Third, measurement method differences: variations across DXA device models introduce BMD measurement error [46],

and different functional assessment tools yield varying sensitivity and specificity for fall prediction [47]. Standardisation of study design is therefore essential to reduce variability.

2.2.4 Gaps in the evidence for long-term community application, smart implementation, and individualisation

Three major evidence gaps persist. First, community long-term application evidence is insufficient: the majority of studies were conducted in controlled laboratory or clinical settings, with only three identified trials taking place in real-world community environments; community adherence rates and post-cessation effect maintenance remain unknown. Second, smart implementation research is absent: no study has systematically integrated intelligent devices and platforms (e.g., app-guided training, wearable sensors) into RT; most wearable devices serve monitoring functions only, and the impact of older adults' technology acceptance on outcomes has not been quantified. Third, individualised strategies are lacking: despite known responder variability, predictive tools to identify who will benefit most from RT are unavailable. These gaps collectively motivate the present study to validate long-term effectiveness in real community settings, explore smart-technology enhancement pathways, and develop individualised intervention tools.

2.3 Smart Elderly Care and mHealth Acceptance Theory (TAM/eHLQ)

2.3.1 The Technology Acceptance Model (TAM) and its application and evolution in healthcare

The Technology Acceptance Model (TAM), proposed by Davis in 1989, posits that technology adoption is determined by two core constructs: perceived usefulness (PU)—the degree to which a user believes that technology will improve task performance—and perceived ease of use (PEOU)—the degree to which using the technology is perceived as effortless. These constructs influence attitude, which in turn shapes behavioural intention and actual use [48].

In healthcare, TAM has been widely applied to evaluate acceptance of health information technologies. Applications include electronic health records (EHR), where PU and PEOU have been identified as key determinants of nurse adoption [49,50]; telemedicine, where both constructs significantly predict usage intention among patients and clinicians [51]; and virtual reality (VR), where extended TAM models incorporating perceived enjoyment, age, and curiosity predict VR adoption in clinical settings [52].

TAM has undergone successive extensions. TAM2 (Venkatesh and Davis, 2000) introduced

social influence processes (subjective norms, image) and cognitive factors (job relevance, output quality) [54]. TAM3 further incorporated individual characteristics (self-efficacy, risk perception), social capital, and organisational factors [55]. In health applications, privacy, security, and usability have been added as domain-specific variables [56]. Recent trends include multidisciplinary integration, the systematic addition of external variables, and cross-cultural validation [57].

2.3.2 The eHealth Literacy Questionnaire (eHLQ) framework and its core dimensions

The eHLQ, developed from the eHealth Literacy Framework (eHLF; Norgaard et al., 2015), is a multidimensional instrument comprising 35 items distributed across seven dimensions on a 4-point Likert scale: (1) ability to access health information; (2) ability to understand health information; (3) ability to appraise health information; (4) technical operational ability; (5) perceived needs-fit of technology; (6) digital health management ability; and (7) electronic social-support ability [58].

Older adults consistently score lower on the eHLQ. In Chinese studies, the mean score for the dimension "using technology to process health information" among adults aged 60+ was 46.67, significantly below that of younger cohorts [59].

2.3.3 Specificities of technology acceptance among older adults: barriers and facilitators

Barriers to technology adoption among older adults include physical limitations (poor vision, reduced finger dexterity), cognitive challenges (difficulty retaining operational steps, fear of errors), psychological resistance (preference for face-to-face interaction), and economic constraints (cost of devices and internet access) [60]. Facilitators include visual demonstration-based training (Techatraiphum et al. (2016) showed that visual demonstrations significantly increased telehealth acceptance), family support, age-friendly design features (large fonts, voice prompts, one-touch emergency buttons), and observable benefits (e.g., video calls with grandchildren) [61].

2.3.4 Constructing a theoretical framework integrating TAM and eHLQ to understand and predict adherence to smart elderly care interventions

The integrated TAM–eHLQ framework proposes the following pathways [62]: foundational capacity (higher eHLQ scores → higher PEOU); value recognition (strong eHLQ "health management ability" → higher PU); actual use (high PEOU + PU → intention to use →

training adherence); and external support (family encouragement increases effect by approximately 50%). This framework guides the present study in three ways: using the eHLQ to assess technological capacity, using TAM items to evaluate perceived usefulness and ease of use, and analysing how technology acceptance influences training attendance.

2.4 Cost-Effectiveness and Health Economics Framework

2.4.1 Basic types of health economic evaluation

Health economic evaluation assists decision-makers in determining whether medical interventions warrant investment. Three principal types exist. Cost-effectiveness analysis (CEA) compares the costs and natural health outcomes of different interventions—for example, the cost per 1% BMD improvement or per fracture prevented. Cost–utility analysis (CUA) uses the quality-adjusted life year (QALY) as the effectiveness unit, combining survival time and quality of life; cost per QALY gained (ICER) enables cross-disease comparison. Cost–benefit analysis (CBA) monetises health outcomes, directly comparing the monetary value of averted fractures with intervention costs; however, the monetisation of health value remains controversial and limits practical application.

2.4.2 The concept, calculation, and interpretation of the incremental cost-effectiveness ratio (ICER)

ICER is the core metric for evaluating the economic merit of an intervention. It is calculated as: ICER = (Cost of intervention group − Cost of control group) / (Effect of intervention group − Effect of control group). For example, if smart RT costs CNY 500 per person, control costs CNY 100, and the intervention group gains 0.05 QALY with no change in controls, then ICER = (500 − 100) / (0.05 − 0) = CNY 8,000/QALY.

ICER must be compared against a willingness-to-pay (WTP) threshold. The internationally accepted benchmark is one to three times per-capita GDP. China's 2024 per-capita GDP of approximately CNY 95,000 [62] yields a threshold of CNY 285,000/QALY (three times GDP). If ICER falls below this threshold, the intervention is considered cost-effective. Special cases: when the intervention is both less costly and more effective (negative ICER), it is "dominant"; when it is costlier and less effective, it should be rejected. Uncertainty is assessed through bootstrap resampling (1,000 iterations) to generate a cost-effectiveness acceptability curve (CEAC).

2.4.3 Current status of economic evaluation of osteoporosis interventions

Pharmacological interventions—bisphosphonates, denosumab, and teriparatide—have been shown to be cost-effective in both men and women [63]. Schousboe et al. (2007) demonstrated cost-effective outcomes for BMD testing followed by bisphosphonate treatment in older men [64]. Fracture Liaison Services (FLS) are cost-effective across sexes [63]; Ito (2020) showed cost-effective osteoporosis screening in older men with a fall history [65]. Non-pharmacological interventions including vitamin D and calcium supplementation are cost-effective in older adults [63]; Hiligsmann et al. (2016) confirmed the cost-effectiveness of vitamin D–fortified dairy for fracture prevention in France [66]; and Johansson et al. (2008) demonstrated cost-effectiveness for community safety-promotion programmes in hip-fracture prevention [67]. Notably, no dedicated economic evaluation of RT exists—a gap this study aims to fill.

2.4.4 Challenges and methodological choices for economic evaluation of community exercise interventions

Community exercise economic evaluation faces five challenges, each paired with a targeted solution.

Challenge 1 — Cost fragmentation: Equipment depreciation, venue fees, and training costs are dispersed across multiple items. Solution: micro-costing with item-by-item accounting (e.g., smart terminal cost divided by 10 user-sessions; community worker time costed at hourly wage).

Challenge 2 — Delayed long-term effects: Fracture prevention requires 5–10 years of observation. Solution: Markov modelling extrapolation based on BMD improvement-to-fracture risk reduction, using FRAX® for risk calculation and assuming a conservative 3-year effect duration.

Challenge 3 — Multidimensional benefits: Exercise simultaneously improves function and psychological wellbeing. Solution: primary analysis using EQ-5D–derived QALYs, supplemented by CEA (ICER per 0.01 g/cm² BMD gain).

Challenge 4 — Adherence effects: Actual participation rates influence cost-effectiveness. Solution: attendance-adjusted costing with subgroup ICER analysis (50% vs. 80% attendance groups).

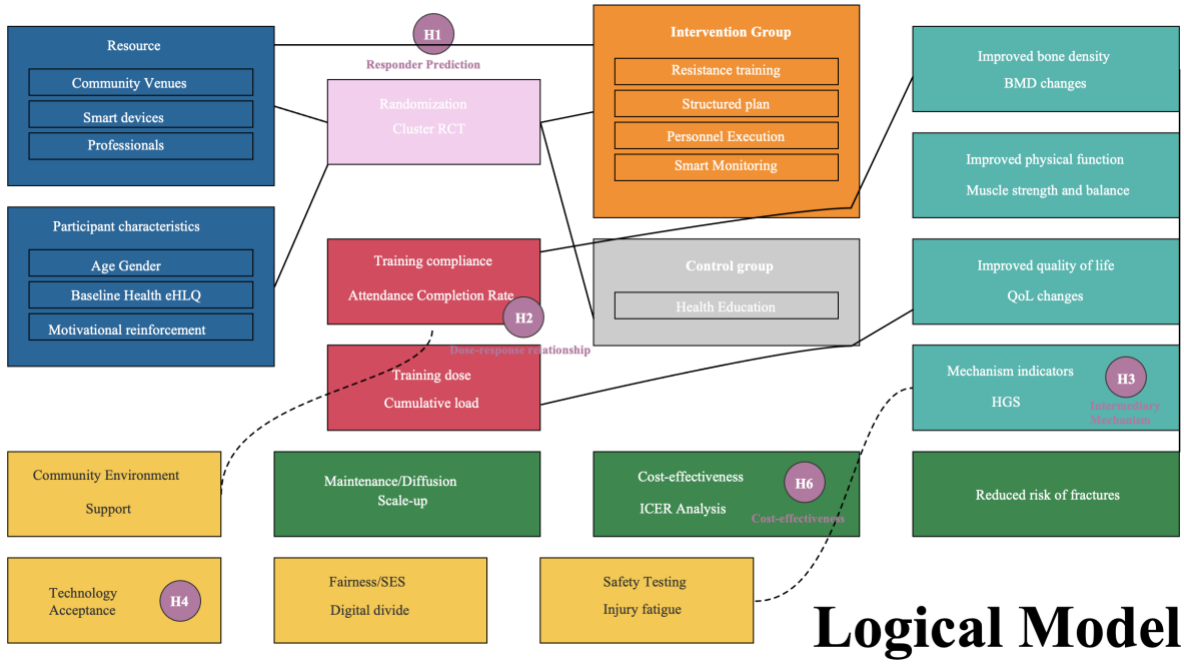
Challenge 5 — High uncertainty: Solution: probabilistic sensitivity analysis assigning

distributions to key parameters (cost ±20%, effect ±10%), with 1,000 Monte Carlo simulations generating CEAC curves.

The final methodological combination: RCT-based collection of 12-month cost/QALY data → Markov model projection of 10-year benefits → probabilistic sensitivity analysis for robustness verification.

Chapter 3 Research Hypotheses and Overall Conceptual Model

3.1 Overall Logic Model



3.1.1 Graphical explanation of core elements

The logic model systematically depicts each component of the research and their interconnections. At the "input" level, the study invests essential resources—community training venues, smart RT equipment, and professional supervisors—while accounting for participant characteristics such as age, sex, baseline health status, and eHealth literacy. The "activities" component refers to the smart RT intervention delivered by trained community workers following prescribed frequency, intensity, and duration protocols. Direct "outputs" include training adherence (attendance rate, training completion rate) and actual training "dose" (cumulative training volume), reflecting intervention execution fidelity. These outputs generate "short-term outcomes": improved BMD, enhanced physical function (muscle strength, balance), and increased QoL scores after 8 months. Mechanistic indicators, notably grip-strength change (ΔHGS), are also monitored to explore the mediating role of muscle strength. In the long term, the intervention is expected to reduce fracture risk and demonstrate "cost-effectiveness" at the health-economic level. Several moderating factors—community environment support, technology acceptance, socioeconomic status, and the digital divide—may influence adherence and effect magnitude.

In Figure 3.1, arrows represent causal pathways: from input resources and participant

characteristics, through the RT intervention, influencing adherence and dose, producing short-term improvements in physical and quality-of-life outcomes, and ultimately accumulating into long-term fracture-risk reduction and cost-effectiveness.

3.1.2 Six sub-studies within the model

The logic model pre-specifies six core pathways corresponding to six sub-studies, each grounded in a specific hypothesis (H1–H6). H1 focuses on predictive factors for intervention response, hypothesising that baseline characteristics and eHLQ scores significantly influence RT responsiveness. H2 addresses dose–response relationships, proposing a nonlinear (J- or U-shaped) association between training dose and outcomes. H3 examines the mediating mechanism, positing that grip-strength improvement (ΔHGS) partially mediates the intervention's effect on BMD. H4 investigates the moderating role of technology acceptance on adherence and outcomes. H5 explores QoL trajectory heterogeneity, anticipating at least two distinct trajectory classes with differential clinical associations. H6 addresses economic evaluation, hypothesising that the ICER falls within an acceptable WTP threshold.

3.2 Primary Research Hypotheses (H1–H6)

3.2.1 H1 (Sub-study 1)

Among older adults with primary OP receiving the smart RT intervention, baseline health status and health literacy differentially influence RT response. Specifically, participants with lower baseline BMD but higher eHLQ/technology acceptance scores are more likely to achieve clinically significant BMD improvement (≥3% lumbar spine increase). The rationale is twofold: lower baseline BMD provides greater room for improvement, and higher health literacy and technology acceptance enable more complete understanding and execution of the training protocol.

3.2.2 H2 (Sub-study 2)

A nonlinear relationship exists between actual RT dose and outcomes, potentially exhibiting a J- or U-shaped curve. Adherence is operationalised as the proportion of planned sessions completed and mean training-intensity attainment; dose is quantified as cumulative resistance-training volume. We expect that as dose increases from low to moderate, outcomes (e.g., BMD change) improve substantially, but beyond a certain high dose, marginal benefits plateau or decline, indicating an optimal dose range.

3.2.3 H3 (Sub-study 3)

Intervention-induced muscle-strength gains significantly mediate BMD improvement. Specifically, grip-strength increase (ΔHGS) partially explains the BMD gains observed in the intervention group, forming the causal chain: smart RT → grip-strength improvement → bone-density enhancement. We estimate that ΔHGS accounts for approximately 30–50% of the total effect of the intervention on BMD.

3.2.4 H4 (Sub-study 4)

Technology acceptance moderates intervention effects, mediated through training adherence. Participants with greater smart-device experience and more positive attitudes towards the training platform maintain higher adherence and achieve greater BMD and functional improvements; conversely, participants lacking technological experience or finding device use difficult may discontinue training, thereby attenuating overall intervention effectiveness.

3.2.5 H5 (Sub-study 5)

QoL trajectories during the 8-month intervention are heterogeneous, classifiable into at least two typical patterns (e.g., “improvement” and “stability”). Participants in the improvement trajectory are hypothesised to achieve superior clinical outcomes (greater BMD gain and functional improvement) compared with those in the stable trajectory, suggesting that subjective QoL improvement and objective health gains co-occur.

3.2.6 H6 (Sub-study 6)

Preliminary incremental cost-effectiveness analysis demonstrates that the additional cost per unit BMD gain from the smart RT intervention, relative to usual health education, falls within an acceptable WTP threshold. Specifically, the ICER (per 0.01 g/cm² lumbar spine BMD gain) is expected not to exceed the threshold derived from domestic health-economic evaluation standards, confirming that the intervention achieves an acceptable balance between resource investment and health returns.

3.3 Operationalisation of Core Variables and Measurement Time Points

3.3.1 Independent variables

Core independent variables include: (1) intervention allocation (smart RT intervention group vs. health education control group), the primary independent variable; (2) baseline

demographic and clinical characteristics (age, sex, education, BMI, T-score, fracture history, comorbidities), serving as covariates; (3) technology acceptance indicators, assessed via the eHLQ and TAM scales; and (4) intervention process indicators—adherence (proportion of sessions completed) and dose (cumulative training volume).

3.3.2 Dependent variables

Primary outcomes: (a) BMD (g/cm²) measured by DXA at the lumbar spine, reported as absolute values and percentage change from baseline; (b) physical function assessed by SPPB total score (0–12), 4-metre gait speed (m/s), and five-times sit-to-stand test (seconds); (c) QoL assessed by SF-36 physical component summary (PCS) and mental component summary (MCS) scores (0–100).

Secondary outcomes: fall incidence (monthly fall diaries and telephone follow-up), Falls Efficacy Scale–International (FES-I, 16–64), grip strength (HGS, kg), and visual analogue scale for pain (VAS, 0–10). Supplementary assessments include TUG, Berg Balance Scale, and the Chinese Osteoporosis Screening Scale (SSS-CN).

Mechanistic indicators: ΔHGS (change in grip strength from baseline to 8 months), analysed as a mediator of BMD improvement.

3.3.3 Covariates and potential confounders

The following covariates will be controlled in the analysis: (a) osteoporosis medication use (type and adherence); (b) comorbidity burden (number of chronic conditions); (c) nutritional and metabolic indicators (calcium and vitamin D intake adequacy); and (d) baseline physical activity level (IPAQ, MET-min/week).

3.3.4 Detailed measurement schedule

表 3.3.4 Data measurement schedule 数据测量时间表

Measurement field 测量领域	Specific measurement items 具体测量项目	T0 Before intervention 干预前	T1 4 months 4 个月	T2 8 months 8 个月	T3 14 months 14 个月	备注
Demography 人口学	Age, gender, education level, medical history, medication use	✓				Baseline collection only
Physical indicators	Height、weight、BMI	✓		✓	✓	Tracking changes

身体指标						
BMD 骨密度 DXA	Lumbar spine and hip BMD	✓	✓	✓	✓	4 months DXA As needed
Body functions 身体功能	SPPB Overall Rating	✓	✓	✓	✓	
	Overall balance	✓	✓	✓	✓	
	4-meter pace	✓	✓	✓	✓	
	5 Sit-to-Stand (5STS)	✓	✓	✓	✓	
	Grip strength（HGS）	✓	✓	✓	✓	Intermediary Indicators
Questionnaire 问卷调查	SF-36	✓	✓	✓	✓	
	FES-1	✓	✓	✓	✓	
	eHLQ、TAM	✓	✓	✓		Track
Implementation process 实施过程	Training compliance and dosage (platform log and manual log)		✓	✓		Continuous recording to stage nodes
Safety Monitoring 安全监测	Cumulative number of falls & adverse events			✓	✓	Summary
	New fracture				✓	
Behavior Tracking 行为追踪	Daily physical activity after intervention				✓	

Measurements are conducted at four time points: T0 (baseline, 1 week pre-randomisation) includes comprehensive demographic, clinical, functional, and questionnaire assessments; T1 (mid-intervention, 4 months) comprises streamlined assessments covering DXA (resources permitting), functional tests, adherence data, and questionnaires; T2 (end of intervention, 8 months) repeats the full baseline assessment battery plus cumulative adverse events; and T3 (follow-up, 20 months) evaluates long-term outcomes including new fractures, BMD maintenance, and post-intervention physical activity.

Chapter 4 Overall Methodology and Ethics

4.1 Study Design Overview

4.1.1 Primary study design

This study employs a two-arm, parallel-group, assessor-blinded randomised controlled trial (RCT), with 1:1 allocation to the intervention and control groups. Outcome assessors are blinded to group assignment to minimise measurement bias. The protocol and reporting adhere to the CONSORT 2010 Statement, including transparent documentation of randomisation sequence generation, allocation concealment, blinding, and participant flow.

4.1.2 Nested sub-study designs

Six sub-studies are nested within the primary RCT framework. Sub-study 1: predictive model development (TRIPOD guidelines). Sub-study 2: observational dose–response analysis (STROBE statement). Sub-study 3: causal mediation analysis using a counterfactual framework. Sub-study 4: interaction-effect analysis via mixed-effects modelling with interaction terms. Sub-study 5: longitudinal trajectory modelling using group-based trajectory modelling (GBTM) or latent class growth modelling (LCGM). Sub-study 6: trial-based economic evaluation with ICER calculation (CHEERS checklist).

4.1.3 Study setting

The study will be conducted at smart community elderly care service centres in Ke'erqin District, Tongliao City, Inner Mongolia Autonomous Region, China. These centres serve typical urban residential communities with large retired populations and established smart elderly care pilot infrastructure. Community sub-district offices will assist with participant recruitment, and licensed rehabilitation therapists will serve as consultants. Tongliao City Hospital orthopaedics department will provide DXA equipment support and medical advisory services.

4.2 Participants

4.2.1 Inclusion criteria

Eligible participants must: (1) be aged ≥60 years (either sex); (2) have a DXA-confirmed diagnosis of primary OP (lumbar spine or hip T-score ≤ −2.5, or ≤ −2.0 with a fragility fracture history); (3) reside in the designated community with no relocation plans within one year; (4) demonstrate adequate cognitive function (MMSE ≥24, adjusted for education level); (5) be

independently ambulatory (assistive devices permitted; severe motor impairments excluded); (6) provide written informed consent; and (7) have confirmed primary OP (secondary OP excluded).

4.2.2 Exclusion criteria

Exclusion criteria include: (1) recent major medical events (fracture, hip/spine surgery within 3 months, or uncontrolled cardiovascular disease within 6 months); (2) current participation in comparable exercise programmes or clinical trials; (3) terminal illness with estimated survival <1 year; (4) inability to complete 12-month follow-up (planned relocation); (5) severe sensory or communication impairments precluding training participation; (6) other conditions deemed unsuitable by investigators (e.g., severe alcohol dependence); and (7) lack of family/caregiver support.

4.2.3 Recruitment process

Recruitment proceeds through multiple community channels. The smart elderly care centre databases collectively cover 8,736 residents aged 60+, of whom 2,619 carry an OP diagnosis. Community sub-district offices co-host health seminars and post recruitment notices; community clinic physicians identify potentially eligible patients. Interested individuals undergo telephone pre-screening. Those preliminarily eligible attend an in-person enrolment assessment at the community centre, where they provide informed consent, undergo inclusion/exclusion verification, and complete baseline evaluations (DXA, functional tests, questionnaires). Eligible participants are then randomised via computer-generated random sequence. The entire process is documented in a CONSORT flow diagram.

4.3 Intervention Protocol and Control Measures

4.3.1 Intervention group (smart community resistance training)

Table 4.3.1 (1), Resistance training program

Program Framework	Implementation Methods	Specific content	
Pre-implementation assessment	The researchers, orthopedic physicians, and nurses jointly evaluated	1. Detailed medical history and physical examination to exclude contraindications to exercise (such as severe cardiovascular disease, history of cerebral infarction, etc.) 2. Muscle function, exercise ability, exercise level, etc. 3. Whether there are diseases that restrict exercise, such as knee osteoarthritis, bone deformity, etc., whether there are mental disorders, intellectual disabilities, etc.	
Resistance Training Program		Exercise intensity	Moderate intensity (12-13 points on the PRE scale)

			- Starting intensity: 50-60% 1RM (RPE 3-4) - After advancement: 70-80% 1RM (RPE 5-6) - Breathing principle: exhale with force, inhale with relaxation
		Exercise frequency	3 times/week, 1-2 sets of each exercise, 10-15 repetitions per set; 1-4 weeks 1 set of each exercise (10-15 repetitions/set) 5-12 weeks 2 sets of each exercise (10-15 repetitions/set) **Based on the training manual**
		Exercise time	5 minutes of warm-up, 40 to 60 minutes of resistance training (including interval rest time, 2 to 3 minutes rest between each set), and 5 minutes of stretching and relaxation.
		Sports Tools	4 types of elastic bands. Yellow is 10 pounds (about 4.5 kg) Pink is 15 pounds (about 6.75 kg) Blue is 20 pounds (about 9.07 kg) Purple is 30 pounds (about 13.6 kg) According to the patient's repetition of 10 to 15 times combined with the PRE dosage to reach a moderate intensity, the elastic band with corresponding load is given.
		Specific actions	1. Warm-up exercises: including neck stretching, chest expansion exercises, hip rotation exercises, knee twisting exercises, and marching in place, etc. 2. Resistance exercises: including waist and back exercises, lower limb exercises, and upper limb exercises. See **Table 4.3.1 (2) for specific resistance exercise movements** 3. Relaxation: stretching, massaging, patting, shaking, and relaxing the limbs with breathing.
		Precautions	1. Do not hold your breath during training to prevent cardiovascular disease 2. When exercising, pay attention to inhaling when exerting force and exhaling when relaxing 3. After exercise, use the smart health bracelet to remind the elderly to fill in the exercise diary.

			4. Before exercise, self-assess whether there are any discomfort symptoms, blood pressure and blood sugar control, and stop exercising if you feel uncomfortable 5. If the patient experiences dizziness, chest tightness, difficulty breathing and other discomfort symptoms during exercise, stop exercising immediately and contact the researcher immediately 6. Gradually increase the intensity of exercise to ensure patient tolerance.
Health Education Program	Expert Lectures	1. Definition, classification and harm of the disease, etc., to make patients aware of the susceptibility of the disease 2. The effect of exercise on osteoporosis and the harm of inactivity, etc., to make patients aware of the benefits of exercise and the severity of inactivity 3. Analyze the patient's current movement disorders, gradually eliminate the obstacles they may encounter, and correct incorrect cognition	
	1 offline group class per month	1. Patients share their current feelings about exercise and the obstacles they encounter 2. Patients with strong exercise execution ability share their experiences 3. Review the effects of exercise 4. Provide supplementary health education	
	Once a week, offline action guidance, error correction and adjustment	1. Ask patients about their individual differences in the implementation of the plan 2. Encourage patients to keep exercising 3. Understand and guide patients on how to master exercise methods, and timely micro-control the amount of exercise 4. Export the patient's health data and exercise status analysis for this week through the smart bracelet data platform and use the data to make patients more confident to continue to persist. 5. Ask patients about their exercise status in the past week and encourage them to express their feelings about exercise. 6. Emphasize precautions during exercise to ensure patient safety	

The intervention follows the FITT-VP exercise prescription principles. Frequency: 3 sessions/week. Time: 5-minute warm-up, 30–50 minutes of RT (including 2–3 minutes inter-set rest), 5-minute cool-down stretching. Type: moderate-intensity whole-body resistance exercises targeting weight-bearing muscle groups. Intensity: initial 50–60% 1RM (RPE 3–4),

progressing to 70–80% 1RM (RPE 5–6). Volume: weeks 1–4, one set per exercise (10–15 repetitions); weeks 5–12, two sets per exercise. Equipment: colour-coded elastic resistance bands (yellow 10 lb/4.5 kg; pink 15 lb/6.75 kg; blue 20 lb/9.07 kg; purple 30 lb/13.6 kg), assigned based on baseline functional assessment.

Table 4.3.1（2），Specific resistance exercise movements 具体抗阻运动动作

	Action name (muscle group exercised)	Key Points
Lower back exercise 腰背部运动		
1	Back stretch (Sacrospinal muscles)	Lie prone, place a pillow under your abdomen, put your arms at your sides, use your back strength to lift your upper body, hold for 3 to 5 seconds, then slowly lower it. Rest for 2 to 3 minutes between sets
Lower limb exercise 下肢运动		
2	Band prone position Knee flexion (hamstrings, etc.)	Lie prone, fix the ankle joint with an elastic band, fix the left leg, bend the right knee as much as possible, hold for 3 to 5 seconds, then slowly lower it. Alternate between left and right for 1 to 2 sets. Rest for 2 to 3 minutes between sets
3	Elastic band supine straight leg raise (quadriceps, etc.)	Supine position, fix the ankle joint with an elastic band, fix the left leg, dorsiflex the ankle joint of the right leg, straighten and lift until you can't go any further, hold for 3 to 5 seconds and then slowly lower, fix the pelvis and lumbar spine with both hands. Alternate between left and right for 1 to 2 sets each. Rest for 2 to 3 minutes between sets
4	Elastic band sitting thigh abduction (gluteus Medius, etc.)	Sit with your hands behind your back, keep your back straight, fix your ankles with an elastic band, straighten your legs, keep your left leg still, and stretch your right leg as far out as possible until you can't go any further, hold for 3 to 5 seconds, then slowly retract. Alternate between left and right for 1 to 2 sets. Rest for 2 to 3 minutes between sets
5	Elastic band seated knee extension (quadriceps, etc.)	Sit on a chair, tighten your abdomen, straighten your back, fix your ankle with an elastic band, keep your left leg still, and stretch your right leg forward. Hold for 3-5 seconds and then slowly lower it. Alternate between left and right for 1-2 sets. Rest for 2-3 minutes between sets.
6	Elastic band ankle plantar flexion (calf muscles)	Sit, fix one end of the elastic band to the forefoot of both feet, tighten the other end with both hands, and plantar flex until you can no longer continue, hold for 3-5 seconds and then slowly put it down. Repeat. Rest 2-3 minutes between sets
7	Elastic band ankle dorsiflexion (dorsiflexor muscles)	Sit down, support yourself with your hands behind your back, fix one end of the elastic band, and put the other end on the instep. Do the dorsiflexion until you can no longer do it. Hold for 3-5 seconds and then slowly lower it. Repeat. Rest for 2-3 minutes between sets.
Upper limb exercise 上肢运动		
8	Band arm raises (deltoids, etc.)	Sit on a chair, tighten your abdomen, straighten your back, face your palms forward, hold the elastic band tightly with both hands and pull it outward wider than your shoulders. After maintaining a certain tension, slowly stretch your hands upwards, hold for 3 to 5 seconds, and then slowly lower them. Rest 2 to 3 minutes between sets
9	Elbow flexion with elastic band (biceps, etc.)	Sit on a chair, tighten your abdomen, straighten your back, put one end of the elastic band on your thigh, hold the other end tightly with your hand, keep your upper arms close to your body and keep them still, slowly pull the elastic band up with your forearms until you can no longer continue, hold for 3-5 seconds,

		then slowly retract. Alternate between left and right for 1-2 sets. Rest for 2-3 minutes between sets

The training programme comprises nine exercises targeting three body regions. Lumbar-dorsal region: prone back extension (erector spinae). Lower extremity: prone knee flexion (hamstrings), supine straight-leg raise (quadriceps), seated hip abduction (gluteus medius), seated knee extension (quadriceps), ankle plantarflexion (posterior calf), and ankle dorsiflexion (anterior tibialis). Upper extremity: seated overhead press (deltoids) and seated biceps curl (biceps brachii).

Periodised progression follows dual-indicator control: volume progression (one additional set per exercise every 4 weeks, maximum 3 sets), intensity progression (resistance-band upgrade when RPE ≤4 with 15 standard repetitions), and density progression (inter-set rest reduced from 120 seconds to 75 seconds after week 12).

Smart components: each participant receives a Huawei Band 10 smart wristband that monitors heart rate, fall events, and blood pressure via Bluetooth synchronisation to the community health management platform. Training completion is recorded through WeChat-based manual check-in. A WeChat mini-programme delivers daily training prescriptions with illustrated guidance. The system includes automated training reminders and safety alerts (abnormal heart-rate detection triggers rest prompts and staff notification).

Personnel support: trained staff provide in-person guidance during the first week, with monthly on-site supervision thereafter. A designated team member contacts each participant weekly via WeChat to address questions and maintain adherence. Health education includes monthly group lectures and weekly one-on-one technique correction sessions.

Safety measures: pre-training medical screening (physical examination and exercise-risk assessment), individualised modifications for comorbidities (e.g., extended warm-up and blood-pressure monitoring for hypertensive patients), on-site emergency equipment (first-aid kit, AED), and a formal adverse-event reporting mechanism with monthly review and immediate reporting of serious events to the ethics committee.

4.3.2 Control group

The control group receives standard health education without systematic RT. Activities include monthly 60-minute bone-health lectures (OP pathophysiology, nutritional guidance, fall-prevention strategies), delivered by hospital orthopaedic and community clinic staff, with

printed educational materials. Group discussion sessions are held every 4 months. Weekly telephone or WeChat follow-up by research staff provides general health advice (e.g., daily 20–30 minute walks), maintaining comparable contact frequency without introducing RT. This "attention control" design ensures that contact and engagement levels are balanced between groups.

4.3.3 Intervention fidelity control

Standardised training: all staff complete a unified training programme covering intervention protocol details, safety procedures, and data-recording requirements, culminating in practical and written examinations. An intervention operations manual specifies step-by-step procedures. Process monitoring: monthly random audits via on-site observation or video-log review assess protocol adherence. The smart platform automatically logs training data for weekly cross-referencing against the planned schedule. Participants complete brief weekly training diaries. Fidelity assessment: a checklist scoring key execution points (warm-up guidance, technique correction, intensity compliance) targets an average score of ≥90%.

4.4 Primary and Secondary Outcome Measures

4.4.1 Primary outcomes (T2)

BMD: Lumbar spine BMD (g/cm²) measured by DXA (e.g., GE Lunar Prodigy), reported as absolute values and percentage change from baseline. Within-day coefficient of variation for lumbar spine BMD is approximately 1%.

Physical function: SPPB total score (0–12), comprising standing balance, 4-metre gait speed, and five-times chair-stand subtests (each scored 0–4).

Quality of life: SF-36 Physical Component Summary (PCS) and Mental Component Summary (MCS), each scored 0–100.

4.4.2 Secondary outcomes

Fall incidence (cumulative falls recorded via smart-terminal feedback and monthly follow-up; incidence rate ratio [IRR] with 95% CI). FES-I (16–64; score ≥23 indicates fear of falling). Grip strength (HGS, kg; measured at T0, T1, T2; ΔHGS used for mediation analysis). Pain (VAS, 0–10). Intervention process and safety indicators: mean training adherence, mean training dose, and adverse-event frequency and severity.

4.4.3 Measurement standardisation

DXA: all scans performed on the same device with daily phantom calibration; L1–L4 region-of-interest placement by certified technicians following a uniform protocol; same-technician longitudinal measurement preferred. Functional assessments: evaluators complete standardised training with inter-rater reliability verified (ICC > 0.90); test conditions (chair height, walkway length) are held constant. Questionnaires: validated Chinese-language versions administered under neutral guidance; immediate completeness checks. Equipment calibration: grip dynamometer calibrated before use; standardised seated position with 90° elbow flexion, best of two trials recorded. Quality assurance: all personnel certified prior to data collection; monthly data-quality meetings address and correct procedural issues.

4.5 Data Management and Quality Control

4.5.1 Data collection

Data are collected primarily through an electronic case report form (eCRF) system. Assessors enter measurements directly into tablet-based electronic forms with pre-defined range and logic checks. Each participant receives a unique identification code; names are excluded to protect privacy and maintain blinding. Paper CRFs serve as backup and undergo double data entry within 24 hours. Real-time backups to a central cloud server (Jianguoyun) are supplemented by weekly offline archives.

4.5.2 Data entry and storage

Dual-entry verification identifies discrepancies for correction against original records. The project database resides on an encrypted cloud server (Jianguoyun) with AES-256 encryption, role-based access control (PI: full access; field assessors: data-entry only), and audit-trail logging. Daily automated backups to an off-site server and weekly encrypted hard-drive archives ensure data security. All procedures comply with China's Personal Information Protection Law; analytical datasets are stripped of direct identifiers.

4.5.3 Data cleaning

Missing data: distributions and patterns are reported for all key variables. Little's MCAR test assesses missingness mechanisms; if data are missing at random (MAR), multiple imputation is used for sensitivity analysis. Linear mixed models in the primary analysis accommodate incomplete data. Outliers: identified through distribution plots and box plots, verified against original records, and handled according to pre-specified rules: confirmed errors are corrected, physiologically implausible values are excluded, and plausible extreme values are retained with

robust or sensitivity analyses (e.g., Winsorisation). All exclusions and modifications are documented.

4.6 Risk Assessment and Mitigation

Risk is scored as Probability (P: 1–3) × Severity (S: 1–3), yielding a risk grade of 1–2 (low), 3–4 (moderate), 5–6 (high), or 7–9 (very high). Ten risk categories are assessed, including training safety (elastic-band breakage, exercise-induced cardiovascular events, falls), adverse-event reporting delays, data privacy, protocol compliance, adherence decline, equipment/IT failures, public health emergencies, and budget constraints. Mitigation measures encompass branded-equipment inspections, baseline PAR-Q screening, continuous heart-rate monitoring, slip-resistant training surfaces, 24-hour SAE dual-channel reporting, AES-256 data encryption, gamified adherence incentives, 10% reserve equipment, contingency home-based training protocols, and 10% contingency budgets.

4.7 Ethical Approval

4.7.1 Ethics committee and approval status

Ethical approval is pending.

4.7.2 Informed consent process

Each candidate receives a plain-language informed consent document. Research staff provide oral, item-by-item explanations covering study purpose, procedures, risks (potential muscle soreness, minimal DXA radiation exposure), and benefits (free BMD reports, personalised exercise guidance). Participation is voluntary; withdrawal is permitted at any stage without consequence. Privacy protections (coded identification, no publication of individual data) are detailed. Following opportunity for questions and discussion, participants sign or fingerprint the consent form, witnessed and co-signed by the investigator.

4.7.3 Data safety and monitoring

An internal safety monitoring mechanism is established: two senior physicians not directly involved in intervention delivery review trial operations and safety data every 4 months. Serious adverse events (e.g., training-related fractures, hospitalisation) trigger immediate review, participant suspension, and risk reassessment before deciding whether to modify or terminate the protocol.

References

[1] Gian Fredi, V., Nucci, D., Pennisi, F. et al. Aging, longevity, and healthy aging: the public health approach. Aging Clin Exp Res 37, 125 (2025). https://doi.org/10.1007/s40520-025-03021-8

[2] Chen, Y. (2024, February 19). *Di qi ci quanguo renkou pucha gongbao [The 7th national population census bulletin]*. The State Council of the People's Republic of China. https://www.gov.cn/guoqing/2021-05/13/content_5606149.htm

[3] Yiming [佚名]. (2019). Zhongguo guzhi shusong zheng liuxingbingxue diaocha ji "jiankang guge" zhuanxiang xingdong jieguo fabu [Epidemiological survey of osteoporosis in China and results of the "Healthy Bone" initiative]. *Zhonghua Guzhi Shusong He Gu Kuangyan Jibing Zazhi [Chinese Journal of Osteoporosis and Bone Mineral Research]*, 12(4), 317–318.

[4] Salari, N., Darvishi, N., Bartina, Y., Larti, M., Kiaei, A., Hemmati, M., Shohaimi, S., & Mohammadi, M. (2021). Global prevalence of osteoporosis among the world older adults: A comprehensive systematic review and meta-analysis. Journal of Orthopaedic Surgery and Research, 16, 669. https://doi.org/10.1186/s13018-021-02821-8

[5] Kanis, J. Assessment of osteoporosis at the primary health-care level. WHO Scientific Group Technical Report. 2007.

[6] Shatrugna, V., et al., Bone status of Indian women from a low-income group and its relationship to the nutritional status. Osteoporos Int, 2005. 16(12): p. 1827-35.

[7] Naso, C. M., Lin, Y., Song, G., & Xue, H. (2025). Time trend analysis of osteoporosis prevalence among adults 50 years of age and older in the USA, 2005–2018. Osteoporosis International, 36(3), 547. https://doi.org/10.1007/s00198-025-07395-3

[8] Zhang, Y., You, R. X., Zhang, C., & The Expert Consensus Writing Group of the Chinese Pharmaceutical Association Hospital Pharmacy Committee. (2024). Guzhi shusong zheng zhiliao yaowu heli yingyong zhuanjia gongshi (2023) [Expert consensus on rational use of drugs for osteoporosis treatment (2023)]. *Zhongguo Yiyuan Yaoxue Zazhi [Chinese Journal of Hospital Pharmacy]*, 44(9), 985–1006.

[9] Global Burden Disease Fracture Collaborators. Global, regional, and national burden of bone fractures in 204 countries and territories,1990-2019: a systematic analysis from the global burden of disease study 2019. Lancet Healthy Longev. 2021;2(9): e580–e592

[10] Sing CW, et al. Global Epidemiology of Hip Fractures: Secular Trends in Incidence Rate, Post-Fracture Treatment, and All-Cause Mortality. J Bone Miner Res. 2023 Aug;38(8):1064-1075. doi: 10.1002/jbmr.4821. Epub 2023 May 29. PMID: 37118993.

[11] Delmas, P.D., et al., Underdiagnosis of vertebral fractures is a worldwide problem: the IMPACT study. J Bone Miner Res, 2005. 20(4): p. 557-63

[12] International Osteoporosis Foundation. Facts and Statistics. Retrieved January 31, 2025, from https://www.osteoporosis.foundation/facts-statistics

[13] People's Daily Overseas Edition. (2020, December 25). Yufang "gu cui cui": Duo xueshu jigou qidong "Guli jihua" [Preventing osteoporosis: Multiple institutions launch the "Bone Power Plan"]. *People's Daily Overseas Edition*, p. 09.

[14] Healthy China Initiative Promotion Committee. (2019). *Healthy China Initiative (2019–2030)*. National Health Commission of China. https://www.nhc.gov.cn/guihuaxxs/c100133/201907/2a6ed52f1c264203b5351bdbbadd2da8.shtml

[15] Ministry of Industry and Information Technology, Ministry of Civil Affairs, & National Health Commission. (2021). *Smart healthcare and elderly care industry development action plan (2021–2025)*. https://www.gov.cn/zhengce/zhengceku/2021-10/23/content_5644434.htm

[16] Central Committee of the Communist Party of China & The State Council. (2024). *Opinions on deepening the reform and development of elderly care services*. https://www.gov.cn/zhengce/202501/content_6996775.htm

[17] Ministry of Civil Affairs. (2023). *2023 National Bulletin on the Development of the Aging Cause*. The State Council of China. https://www.gov.cn/lianbo/bumen/202410/content_6979487.htm

[18] Ministry of Industry and Information Technology, Ministry of Civil Affairs, & National Health Commission. (2025). *Notice on the Publication of the "Catalogue of Smart Health and Elderly Care Products and Services (2024 Edition)"*. https://www.miit.gov.cn/zwgk/zcwj/wjfb/tg/art/2025/art_bfa9511fecfb4b22b804f82d5f864690.html

[19] State Administration for Market Regulation. (2025). *China leads release of international standard for elderly care robots*. The State Council of China. https://www.gov.cn/lianbo/bumen/202503/content_7010124.htm

[20] Hong, A. R., & Kim, S. W. (2018). Effects of Resistance Exercise on Bone Health. Endocrinology and Metabolism, 33(4), 435. https://doi.org/10.3803/EnM.2018.33.4.435

[21] Borde, R., Hortobágyi, T. & Granacher, U. Dose–Response Relationships of Resistance Training in Healthy Old Adults: A Systematic Review and Meta-Analysis. Sports Med 45, 1693–1720 (2015). https://doi.org/10.1007/s40279-015-0385-9

[22] Hu, L., Chen, W., Qian, A., & Li, Y. (2024). Wnt/β-catenin signaling components and mechanisms in bone formation, homeostasis, and disease. Bone Research, 12(1), 1-33. https://doi.org/10.1038/s41413-024-00342-8

[23] Yang, L. J., Li, Q., Feng, L., Wu, S. M., Li, J. F., Song, Q., Li, Q., Li, L., Li, M., Li, H., Li, J., Li, H., Li, G., Li, F., Li, D., Li, C., Li, W., & Li, L. (2024). The effect of blood flow restriction and progressive resistance training on elderly patients with type 2 diabetes mellitus and sarcopenia. *Shiyong Laonian Yixue [Practical Geriatric Medicine]*, 38(11), 1129–1135.

[24] Rabinovich, R., & Raurich, J. M. (2021). Isotonic quadriceps endurance is better associated with daily mobility in COPD than isometric quadriceps strength. PLOS ONE, 16(5), e0247673. https://pmc.ncbi.nlm.nih.gov/articles/PMC8172909/

[25] Ni, H. J., Hsu, T. F., Chen, L. K., et al. (2022). Effects of exercise programs in older adults with muscle wasting: A systematic review and meta - analysis: Effects of exercise programs in muscle wasting. Arch Gerontol Geriatr, 99, 104605. https://doi.org/10.1016/j.archger.2021.104605

[26] Mende, E., Moennia, N., Schaller, N., et al. (2022). Progressive machine - based resistance training for prevention and treatment of sarcopenia in the oldest old: A systematic review and meta - analysis. Exp Gerontol, 163, 111767. https://doi.org/10.1016/j.exger.2022.111767.

[27] Wu, C. M., & Sun, J. Z. (2021). Meta-analysis of lower limb resistance training on walking and balance ability in the elderly. *Zhongguo Zuzhi Gongcheng Yanjiu [Chinese Journal of Tissue Engineering Research]*, 25(26), 4257–4264.

[28] M., L., Carranza, S. T., Ángel, M., Diaz, R., & Ortega, M. A. (2023). The RANK–RANKL–OPG System: A Multifaceted Regulator of Homeostasis, Immunity, and Cancer. Medicina, 59(10), 1752. https://doi.org/10.3390/medicina59101752

[29] Zhang, Y., Yu, X., Zhou, C., Fu, K., Luo, H., & Wu, C. (2023). Targeting cellular senescence in senile osteoporosis: Therapeutic potential of traditional Chinese medicine. Frontiers in Medicine, 10, 1288993. https://doi.org/10.3389/fmed.2023.1288993

[30] Shim, J., Iwaya, C., Ambrose, C. G., Suzuki, A., & Iwata, J. (2022). Micro-computed tomography assessment of bone structure in aging mice. Scientific Reports, 12(1), 1-16. https://doi.org/10.1038/s41598-022-11965-4

[31] Blemker, S. S., Brooks, S. V., Esser, K. A., & Saul, K. R. (2023). Fiber-type traps: Revisiting common misconceptions about skeletal muscle fiber types with application to motor control, biomechanics, physiology, and biology. Journal of Applied Physiology. https://doi.org/JAPPL-00337-2023

[32] Breuillard, C., Le Plénier, S., Guihenneuc, C., Choisy, C., Hourdé, C., & Moinard, C. (2025). Nutritional modulation of the mTORC1 pathway in muscle: Differential effect according to muscle and sex. American Journal of Physiology-Regulatory, Integrative and Comparative Physiology. https://doi.org/R-00156-2024

[33] Palaiothodorou, D., Vagenas, G. Inter-arm bone mass and size asymmetries in children tennis players are maturity status specific: a 9-month study on the effects of training time across pubertal change and somatic growth. Eur J Appl Physiol 124, 2081–2092 (2024). https://doi.org/10.1007/s00421-024-05425-2

[34] Paoletti, I., & Coccurello, R. (2023). Irisin: A Multifaceted Hormone Bridging Exercise and Disease Pathophysiology. International Journal of Molecular Sciences, 25(24), 13480. https://doi.org/10.3390/ijms252413480

[35] Pan, Y., Li, X., Chen, Y., Li, X., & Wang, J. (2021). Insulin-like growth factor-1 promotes the proliferation and osteogenic differentiation of bone marrow mesenchymal stem cells through the Wnt/β-catenin pathway. Experimental and Therapeutic Medicine, 22(6), 2339-2352. https://doi.org/10.3892/etm.2021.10323

[36] Tøien, T., Nielsen, J. L., Berg, O. K., Brobakken, M. F., Nyberg, S. K., Espedal, L., Malmo, T., Frandsen, U., Aagaard, P., & Wang, E. (2023). The impact of life-long strength versus endurance training on muscle fiber morphology and phenotype composition in older men. Journal of Applied Physiology. https://doi.org/JAPPL-00208-2023

[37] Zebaze, R., Atkinson, E. J., Peng, Y., Bui, M., Khosla, S., & Seeman, E. (2018). Increased Cortical Porosity and Reduced Trabecular Density Are Not Necessarily Synonymous With Bone Loss and Microstructural Deterioration. JBMR Plus, 3(4), e10078. https://doi.org/10.1002/jbm4.10078

[38] Xiaoya, L., Junpeng, Z., Li, X., Haoyang, Z., Xueying, F., & Yu, W. (2025). Effect of different types of exercise on bone mineral density in postmenopausal women: A systematic review and network meta-analysis. Scientific Reports, 15(1), 1-10. https://doi.org/10.1038/s41598-025-94510-3

[39] Nejatiyan, A., Ahmadi, S., & Wu, M. (2025). The influence of resistance training on inflammatory markers, body composition, and functional capacity in healthy older adults: A systematic review and meta-analysis. *Archives of Gerontology and Geriatrics*, 130, Article 105731. https://doi.org/10.1016/j.archger.2024.105731

[40] Gao, J., Fu, X., Xu, H., Guo, Q., & Wang, X. (2025). The effect of instability resistance training on balance ability among athletes: A systematic review. Frontiers in Physiology, 15, 1434918. https://doi.org/10.3389/fphys.2024.1434918

[41] Dormosh, N., Heymans, M. W., Schut, M. C., Medlock, S., & Van Schoor, N. M. (2024). A systematic review of fall prediction models for community-dwelling older adults: Comparison between models based on research cohorts and models based on routinely collected data. Age and Ageing, 53(7). https://doi.org/10.1093/ageing/afae131

[42] Zhao, F., Su, W., Sun, Y. et al. Optimal resistance training parameters for improving bone mineral density in postmenopausal women: a systematic review and meta-analysis. J Orthop Surg Res 20, 523 (2025). https://doi.org/10.1186/s13018-025-05890-1

[43] Liu, Cj., Shiroy, D.M., Jones, L.Y. et al. Systematic review of functional training on muscle strength, physical functioning, and activities of daily living in older adults. Eur Rev Aging Phys Act 11, 95–106 (2014). https://doi.org/10.1007/s11556-014-0144-1

[44] Li, Y. Y., Qu, X. L., Hu, J. Q., Nie, T. T., & Wu, L. (2022). Application of progressive resistance elastic band training in lower limb muscle strength and balance training among elderly stroke patients with hemiplegia. *Zhongguo Linchuang Weisheng Zazhi [Chinese Journal of Clinical Healthcare]*, 25(3). https://doi.org/10.3969/j.issn.1672-6790.2022.03.028

[45] Gates, A. T., Mertz, K. H., Bloch-Ibenfeldt, M., Garde, E., Baekgaard, M., Svensson, R. B., & Kjaer, M. (2021). Different training responses in elderly men and women following a prolonged muscle resistance training intervention. Translational Sports Medicine, 4(6), 892-899. https://doi.org/10.1002/tsm2.293

[46] Shepherd, J. A., Morgan, S. L., & Lu, Y. (2008). Comparing BMD results between two similar DXA systems using the generalized least significant change. Journal of clinical DENSITOMETRY: the official journal of the International Society for Clinical Densitometry, 11(2), 237–242. https://doi.org/10.1016/j.jocd.2008.02.001

[47] Omaña, H., Bezaire, K., Brady, K., Davies, J., Louwagie, N., Power, S., Santin, S., & Hunter, S. W. (2021). Functional Reach Test, Single-Leg Stance Test, and Tinetti Performance-Oriented Mobility Assessment for the Prediction of Falls in Older Adults: A Systematic Review. Physical therapy, 101(10), pzab173. https://doi.org/10.1093/ptj/pzab173

[48] Davis, F. D., Bagozzi, R. P., & Warshaw, P. R. (1989). User acceptance of computer technology: a comparison of two theoretical models. Management Science, 35(8), 982-1003，https://pubsonline.informs.org/doi/10.1287/mnsc.35.8.982

[49] Nov, O., & Schecter, W. (2012). Dispositional resistance to change and hospital physicians' use of electronic medical records: A multidimensional perspective. Journal of the American Society for Information Science and Technology, 63(4), 648-656. https://doi.org/10.1002/asi.22602

[50] Morton, M. E., & Wiedenbeck, S. (2009). EHR Acceptance Factors in Ambulatory Care: A Survey of Physician Perceptions. Perspectives in Health Information Management / AHIMA, American Health Information Management Association, 7(Winter), 1c. https://pmc.ncbi.nlm.nih.gov/articles/PMC2805555/

[51] Holtz B, Mitchell K, Hirko K, Ford S，Using the Technology Acceptance Model to Characterize Barriers and Opportunities of Telemedicine in Rural Populations: Survey and Interview Study JMIR Form Res 2022;6(4):e35130，https://formative.jmir.org/2022/4/e35130

[52] Wang, E. Y., Kennedy, K. M., Zhang, L., Qian, D., Forbes, T., Li, B. S., Domingue, B., & Caruso, T. J. (2023). Predicting pediatric healthcare provider use of virtual reality using a technology acceptance model. JAMIA Open, 6(3). https://doi.org/10.1093/jamiaopen/ooad076

[53] Zobair, K. M., Sanzogni, L., Houghton, L., Sandhu, K., & Islam, M. J. . (2021). Health Seekers' Acceptance and Adoption Determinants of Telemedicine in Emerging Economies. Australasian Journal of Information Systems, 25. https://doi.org/10.3127/ajis.v25i0.3071

[54] Venkatesh, V., & Davis, F. D. (2000). A theoretical extension of the technology acceptance model: Four longitudinal field studies. Management science, 46(2), 186-204. https://pubsonline.informs.org/doi/abs/10.1287/mnsc.46.2.186.11926

[55] Walczak, R., & Hawrysz, L. (2021). Use of Telemedicine Technology among General Practitioners during COVID-19: A Modified Technology Acceptance Model Study in Poland. International Journal of Environmental Research and Public Health, 19(17), 10937. https://doi.org/10.3390/ijerph191710937

[56] Alsyouf, A., Lutfi, A., Alsubahi, N., Alhazmi, F. N., Al-Mugheed, K., Anshasi, R. J., Alharbi, N. I., & Albugami, M. (2023). The Use of a Technology Acceptance Model (TAM) to Predict Patients' Usage of a Personal Health Record System: The Role of Security, Privacy, and Usability. International journal of environmental research and public health, 20(2), 1347. https://doi.org/10.3390/ijerph20021347

[57] Walczak, R., & Hawrysz, L. (2021). Use of Telemedicine Technology among General Practitioners during COVID-19: A Modified Technology Acceptance Model Study in Poland. International Journal of Environmental Research and Public Health, 19(17), 10937. https://doi.org/10.3390/ijerph191710937

[58] Kayser, L., Karnoe, A., Furstrand, D., Batterham, R., Christensen, K. B., Elsworth, G., & Osborne, R. H. (2018). A multidimensional tool based on the eHealth literacy framework: development and initial validity testing of the eHealth literacy questionnaire (eHLQ). Journal of medical Internet research, 20(2), e36.

[59] Shi, Z., Du, X., Li, J., Hou, R., Sun, J., & Marohabutr, T. (2024). Factors influencing digital health literacy among older adults: A scoping review. Frontiers in Public Health, 12, 1447747. https://doi.org/10.3389/fpubh.2024.1447747

[60] Almulhem, J. A. (2022). Factors, Barriers, and Recommendations Related to Mobile Health Acceptance among the Elderly in Saudi Arabia: A Qualitative Study. Healthcare, 11(23), 3024. https://doi.org/10.3390/healthcare11233024

[61] Yang, H. J., Lee, J. H., & Lee, W. (2025). Factors influencing health care technology acceptance in older adults based on the technology acceptance model and the unified theory of acceptance and use of technology: meta-analysis. Journal of Medical Internet Research, 27, e65269.

[62] National Bureau of Statistics of China. (2025). Statistical Communiqué of the People's Republic of China on the 2024 National Economic and Social Development. Retrieved from https://www.stats.gov.cn/sj/zxfb/202502/t20250228_1958817.html

[63] Li, N., Beaudart, C., Cauley, J.A. et al. Cost Effectiveness Analyses of Interventions for Osteoporosis in Men: A Systematic Literature Review. PharmacoEconomics 41, 363–391 (2023). https://doi.org/10.1007/s40273-022-01239-2

[64] Schousboe, J. T., Taylor, B. C., Fink, H. A., Kane, R. L., Cummings, S. R., Orwoll, E. S., ... & Ensrud, K. E. (2007). Cost-effectiveness of bone densitometry followed by treatment of osteoporosis in older men. Jama, 298(6), 629-637. https://jamanetwork.com/journals/jama/fullarticle/208348

[65] Ito K. Cost-effectiveness of screening for osteoporosis in older men with a history of falls. JAMA Netw Open. 2020;3(12):e2027584. https://doi.org/10.1001/jamanetworkopen.2020.27584

[66] Hiligsmann M, Burlet N, Fardellone P, Al-Daghri N, Reginster JY. Public health impact and economic evaluation of vitamin D-fortified dairy products for fracture prevention in France. Osteoporos Int. 2017;28(3):833–40. https://doi.org/10.1007/s00198-016-3786-1

[67] Johansson P, Sadigh S, Tillgren P, Rehnberg C. Non-pharmaceutical prevention of hip fractures: a cost-effectiveness analysis of a community-based elderly safety promotion program in Sweden. Cost Eff Resour Alloc. 2008;6:1–12. https://doi.org/10.1186/1478-7547-6-11.

[68] Martins, L. C. (1999). Did Sutton and Boveri propose the so-called Sutton-Boveri chromosome hypothesis? Genetics and Molecular Biology, 22, 261-272.https://doi.org/10.1590/S1415-47571999000200022

[69] American College of Sports Medicine. (2022). ACSM's Guidelines for Exercise Testing and Prescription (12th ed.). Wolters Kluwer.

[70] Nam, J., Perera, P., Gordon, R., Jeong, Y., Blazek, A., Kim, D., Tee, B., Sun, Z., Eubank, T., Zhao, Y., Labelbecioglu, B., Liu, S., Litsky, A., Weisleder, N., Lee, B., Butterfield, T., Schneyer, A., & Agarwal, S. (2015). Follistatin-like 3 is a mediator of exercise-driven bone formation and strengthening. *Bone*, 78, 62–70. https://doi.org/10.1016/j.bone.2015.04.038

[71] Roppolo, M., Kunnen, E. S., Van Geert, P. L., & Mulasso, A. (2015). A quantitative dynamic systems model of health-related quality of life among older adults. Clinical Interventions in Aging, 10, 1755–1770. https://doi.org/10.2147/CIA.S91605

[72] Akanni, O., Smith, M. L., & Ory, M. G. (2017). Cost-Effectiveness of a Community Exercise and Nutrition Program for Older Adults: Texercise Select. International Journal of Environmental Research and Public Health, 14(5), 545. https://doi.org/10.3390/ijerph14050545

Appendices

Participant Informed Consent Form

Informed Consent Form

Dear Participant；

You are invited to participate in this study. Your participation is entirely voluntary. You may refuse to participate or withdraw at any time without any penalty.

Before making your decision, you should understand the purpose of this study, the potential risks and benefits involved, and what is expected of you. You may also discuss this study and consent form with your family, friends, or physician. If you have any questions about this study or the content of this form, please contact the principal investigator or collaborating institutions. If you decide to participate, you must sign this informed consent form. A signed copy will be provided to you for your records.

1. What is the purpose of this study?

You are invited to participate in this study. The findings will help us understand the effects and mechanisms of resistance training within smart elderly care communities on older adults with primary osteoporosis and provide scientific guidance for such interventions.

2. What do you need to do in this study?

① Participants in the intervention group will wear a smart wristband and perform 2–3 sessions of resistance training per week, with regular follow-up, either at home or in a community center.

② Participants in the control group will continue daily activities and attend regular health education lectures.

3. How long will your participation last?

The study will last approximately 32 weeks (8 months), during which participants will perform resistance training 2–3 times per week, for about 40–60 minutes per session.

4. What are the possible risks or discomforts?

Top academic journals have reported that scientifically designed resistance training is safe. Research shows resistance training improves bone density and physical function in older adults, including muscle strength and balance. Many official guidelines and studies recommend resistance training for treating or alleviating osteoporosis in older adults. If you experience any discomfort during training, the activity will be stopped immediately, and the smart community staff will be notified.

5. What are the potential benefits of participating in this study?

① Improve muscle mass and strength in older adults, prevent age-related sarcopenia, osteoporosis, and falls.

② Receive personal reports on strength, physical ability, and quality of life.

③ Learn to use age-friendly electronic devices and acquire scientific knowledge about resistance training and osteoporosis.

6. Will you receive any compensation for participating in this study?

Yes, you will receive appropriate compensation for participating in this study. Participants in the intervention group who complete all assessments will be rewarded with two free bone mineral density (BMD) scans. Those who complete the full 32-week resistance training program with excellent compliance will be granted ownership of the smart wristband and receive 12 free sessions of community-based physical therapy services in 2026 (one session per month). Participants who withdraw from the study midway must return the smart wristband and will receive a service voucher for the smart community, prorated based on the number of weeks they completed.

7. What if you are injured due to participation?

If you suffer any organic injury as a result of participation in this study, the community and researchers will not provide financial compensation or medical expense coverage. Signing this consent form does not waive any of your legal rights.

8. Can you leave the study midway?

Yes. You may withdraw at any time without penalty.

Researchers or regulatory authorities (such as the ethics committee) may remove you from the study without your consent for the following reasons:

(1) You no longer meet the study requirements;
(2) The study is terminated;
(3) Participation is deemed harmful to your health.

9. How will your personal information be protected?

A unique code will be used to identify your data. This code will not be shared with anyone except where permitted by law.

Your research records will be stored securely so that only study researchers have access unless otherwise required by law. All paper records will be kept in locked drawers. Only researchers have keys. Digital records will be password protected, with passwords known only to the research team.

Your research records will be retained for at least three years after the study ends. The study results may be published in books or academic journals or used for teaching. Your name or other identifiable information will not be disclosed unless you sign a separate form granting permission.

10. Who can you contact if you have questions?

If you have any questions, concerns, or complaints about your participation or your rights as a participant, please contact the principal investigator or the community staff.

Principal Investigator Contact Number: [**********]

I have read this informed consent form, and all my questions have been answered. I voluntarily agree to participate in this study and have received a signed copy of this form.

Participant Name	**Participant Signature**	**Date**

Investigator Name	**Investigator Signature**	**Date**