Review

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Review

Advancements in the Anti-Aging Effects of Physical Activity: Bibliometric- and Meta-Analyses

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Abstract: Objectives: Accumulating evidence suggests that physical activity (PA) is an efficient intervention to maintain functional capabilities and mitigate physiological changes in the older population. However, an attempt has yet to be made to comprehensively investigate the published landscape on the subject. Methods: This study had two aims. The first aim was to perform a bibliometric analysis for two keywords, "aging" and "PA", to analyze the research trend. Since 'frailty' is the most noticeable co-occurring keyword with the two keywords, the second aim was to investigate the effects of PA, particularly resistance training (RT), on frailty via meta-analysis to provide a summary of the current evidence base. Results: Bibliometric analysis revealed that the number of publications on this research topic has gradually increased, highlighting the importance of understanding the role of PA in aging. A meta-analysis found that RT had significant beneficial effects on physical frailty factors, including handgrip strength, lower limb strength, balance, gait speed, and stair climbing ability. Conclusion: These findings demonstrate that RT is an effective intervention for improving physical function in frail populations; thus it has important implications for the development of PA programs for older adults with frailty. Future research is warranted to explore the optimal dose, frequency, and duration of RT programs for older adults, as well as the potential benefits of combining RT with other forms of PA, such as aerobic or balance exercises.

Keywords: aging; physical activity; bibliometric analysis; meta-analysis; frailty; resistance training

1. Introduction

Aging is a natural biological process that results in a progressive decline in physical and cognitive functions [1,2]. A significant consequence of aging is its association with physical inactivity or disuse, resulting in a decline in muscle mass, structure, and strength [3]. This leads to changes in the quantity and quality of skeletal muscles, which can worsen muscle weakness and disability in the older population [4]. Accordingly, physical disability affects a substantial proportion of older adults, with 44% of those aged 65 years or older experiencing physical weakness, thereby increasing the risk of impairments in activities of daily living by 54% [5].

As the global population ages, there is a growing focus among healthcare providers to understand and intervene in the factors that increase the risk of health and functional declines in older adults [6,7]. Frailty syndrome, a clinical state characterized by increased vulnerability to stressors, leading to negative health-related outcomes in individuals [8], represents instability and the risk of current or further loss of function [9]. The frequency of frailty syndrome increases with age and is more prevalent among individuals with disabilities, depression, hip fractures, and other comorbidities, such as cardiovascular disease and nervous system disorders [10]. Therefore, maintaining physical health and functional capacity in older adults is a critical public health concern.

Regular physical activity (PA) has emerged as an efficient intervention for promoting healthy aging [11], as supported by numerous studies highlighting the benefits of various PA interventions in older adults [12,13]. PA can serve as a polypill that improves health-related quality of life and functional capabilities while mitigating the physiological changes and comorbidities associated with aging [14]. It is also a fundamental component of therapeutic strategies targeting age-related muscle loss [15,16]. Over the past few decades, studies have explored the role of PA as a determinant of successful aging in the health and functional status of older individuals have been accumulated [17]. Nevertheless, it is still challenging to synthesize findings, identify prominent trends, and identify research gaps in this research area despite the abundance of literature.

Quantitative bibliographic analysis, a methodology that uses statistical tools and techniques to analyze and interpret bibliographic data [18], can be a valuable approach to understanding research trends in this area [19,20]. An analysis of keywords used by authors or the content of published papers can reveal present and potential future trends in a research area, and the use of bibliometric analysis is becoming more widespread in various research fields [18]. Thus, the first aim of this study was to perform a quantitative bibliographic analysis using the keywords, "aging" and "PA". Specifically, this study focuses on using keyword network analysis to map the connections between two keywords and others and to identify the most noticeable themes and research gaps. Based on the findings of the bibliometric analysis, a prominent co-occurring keyword (herein "frailty") with aging and PA was selected. For the second aim, a meta-analysis of studies exploring the effects of PA on frailty was conducted to synthesize the findings of previous studies and provide a comprehensive summary of the current evidence base.

The findings of this study would have several implications for researchers, healthcare professionals, and policymakers working to promote healthy aging through PA interventions. First, by identifying the most prominent research trends and gaps through bibliometric analysis, this study can guide future research in this area. Second, this study provides a comprehensive summary of the current evidence, informing the development of evidence-based practice guidelines for PA interventions in older adults. Therefore, this study raises awareness of the importance of PA as a key intervention for promoting healthy aging and highlights the need for further research and investment in this field.

2. Materials and Methods

2.1. Bibliometric analysis method

Articles containing the two keywords, "aging" (including aged, old age, old adults, older adult, older people, senior, etc.) and "PA" (including exercise, resistance training, aerobic training, endurance training, and physical fitness) from January 1991 to July 2023 were searched in the SCOPUS, Web of science, and PubMed. The search was performed on August 01, 2023.

Data extraction initially selected 9,088 papers from SCOPUS, 9,925 from Web of Science, and 4,178 from PubMed. After merging these papers and removing duplicates, 14,840 papers constitute the primary body of the literature. The collected studies were further selected by excluding duplicates and non-original research, and 12,859 publications met the inclusion criteria (Figure 1).

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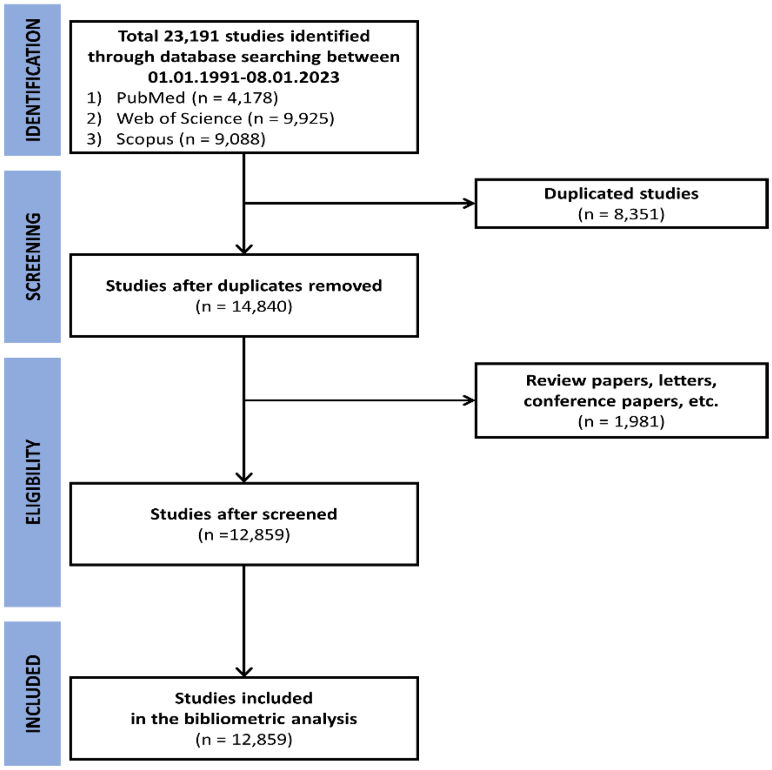

Figure 1. Flowchart of bibliometric analysis selection.

The keywords extracted from the final publications were reviewed by two researchers (YC and DK), where standardized similar words were examined to unify the terms among the evaluators. Keyword analysis and network visualization were performed using VOSviewer 1.6.18 [21].

2.2. Meta-analysis method

Since the results from bibliometric analysis indicate that "frailty" is the prominently growing co-occurring keyword with aging and PA research (see Table 1), we further conducted a meta-analysis for studies investigating the effect of PA, in particular resistance training (RT) known to reduce frailty [22], on old frail individuals from January 1991 to July 2023. This meta-analysis was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement [23]. We used the following keywords: (aging OR aged OR older people OR elderly OR old age OR older adult OR senior) AND (frailty OR frail elderly OR frail OR pre-frail OR pre-frail elderly OR frail older adults OR frail older) AND (resistance training OR resistance exercise OR weightlifting OR strengthening programs OR strength training OR strength exercise OR weight training OR weight exercise). Electronic database searches were performed on August 1, 2023. After identifying 911 potential studies through an initial search using three search engines (281 articles from PubMed, 328 articles from Web of Science, and 302 articles from Scopus), 217 duplicate studies were excluded. We excluded 895 studies on the basis of the inclusion and exclusion criteria. The inclusion criteria were: (1) studies that recruited older adults (age ≥65) with pre-frailty or frailty but without comorbid conditions (e.g., diabetes, cancer, stroke, dementia, and depression); (2) studies that estimated the quantitative changes in outcome of interests (body composition, muscular strength, balance, and agility); (3) resistance training intervention lasted ≥ 8 weeks as this is the recommended minimum intervention duration to increase muscle strength [24], and (4) manuscript published in English. The exclusion criteria were as follows: (1) cognitive or social frailty, (2) disability (e.g., advanced disability in performing daily activities, dementia, or end-stage disease), and (3) use of supplements. Finally, the remaining 18 studies [25–42] only with a randomized controlled trial design were selected for the meta-analysis, as shown in the PRISMA flow diagram (Figure 2).

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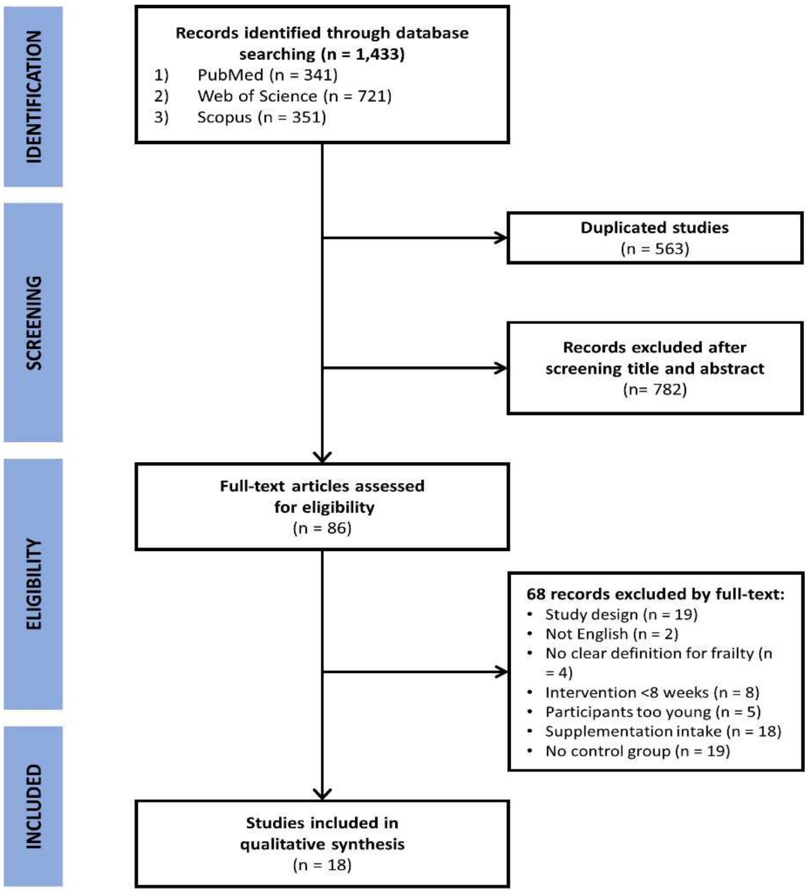

Figure 2. PRISMA flowchart for the study identification procedure of meta-analysis.

2.2.1. Data Extraction

The following variables from the included studies were extracted independently by two authors (YC and DK): (1) characteristics of the study (year of publication, geographical area) and the sample (size, sex, and age); (2) description of the program conducted by the training and control groups; (3) main outcomes of interest; and (4) the overall effect of the outcome of interest. For quantitative analyses (meta-analyses), we collected the group size and mean differences in the outcomes of interest with a 95% confidence interval (CI) or standard deviation (SD) for both groups (intervention and control). All the data were tabulated in an Excel spreadsheet (Microsoft Corporation, Redmond, WA, USA) designed for the meta-analysis. Coding sheets were cross-checked between the authors, and discussions and consensus resolved any discrepancies.

2.2.2. Statistical Analysis

The intervention effect was described as a standardized mean difference (SMD) with a 95% confidence interval (CI). The SMD is a point estimate of the effect of a treatment. Small, moderate, and large effect sizes were defined as values of 0.2–0.49, 0.5–0.79, and >0.79, respectively. I^2 was used to evaluate the between-study heterogeneity. Values of I2 more than 25%, 50%, and 75% were selected to reflect low, moderate, and high heterogeneity, respectively. Random-effect models were used in all meta-analyses because of large variations in the included studies. $p<0.05$ indicated statistical significance. All analyses were performed using meta (version 2.0) and metafor (version 2.0-0) in R version 3.4.4 (The R Foundation for Statistical Computing, Vienna, Austria).

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2.2.3. Quality Assessment

Each study was critically appraised for methodological quality using the Physiotherapy Evidence Database (PEDro) scale (0–10). The PEDro scale is an instrument to assess randomized, controlled trials, with classifications of "poor" (scores 0–3), "fair" (4–5), "good" (6–8), and "excellent" (9–10). Higher PEDro scores indicated better quality, and trials with scores < 4 were excluded.

3. Results

3.1. Bibliometric analysis

3.1.1. Trend of publication year-wise

The number of articles published per year that included these two keywords is shown in Figure 3. The number of publications has gradually increased over time. Although this increasing trend could also be associated with a general increase in the number of researchers and articles published on any subject every year, it is to be noted that 6,029 out of 12,859 articles are published in the past six years (2017–2023). This demonstrates an increasing trend in aging and PA, which is becoming increasingly important on a global scale.

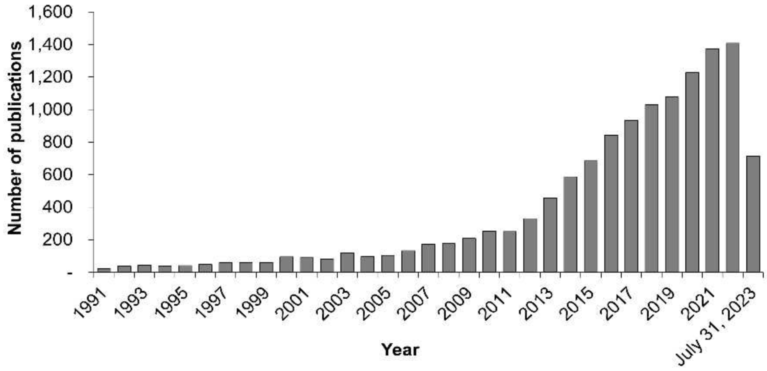

Figure 3. The number of publications having two keywords, 'aging' and 'physical activity' each year between January 1991 and July 2023.

3.1.2. Keywords analysis

We analyzed 15,494 author keywords from 12,859 articles including the two keywords. Figure 4 visually represents the network of these keywords and illustrates the strength of their associations based on the number of articles in which they appeared together [43]. The similarity between two words is proportional to the number of simultaneous occurrences, placing words with high similarity close to each other. The size of the circles representing keywords increases with the relevance of these words, and the distinctive colors of the circles and lines indicate differences in modularity. The thicker the line connecting the two keywords, the stronger their association [44]. After trimming for a minimum of 60 co-occurrences, 98 keywords were shortlisted.

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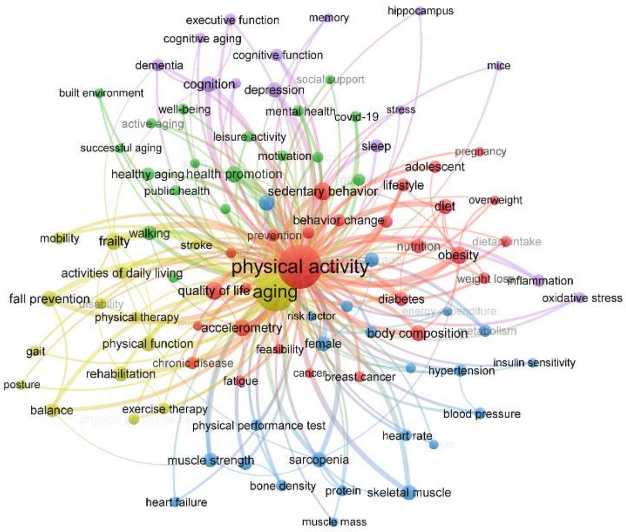

Figure 4. The keyword network from original articles having two keywords, 'aging; and 'physical activity' published between January 1991 and July 2023 (appeared ≥ 60 times). The similarity between two keywords is proportional to the number of simultaneous occurrences, placing words with high similarity close together. The size of the circles representing keywords increases with the relevance of these keywords (total link strength), and the distinctive colors of the circles and lines mean the difference in modularity.

Among these keywords, "sedentary behavior," "quality of life," "obesity," and "frailty" emerged as the most frequently co-occurring terms. They were also closely associated with other keywords, such as "balance," "activities of daily living," "fall prevention," "muscle strength," "walking," and "health promotion."

Furthermore, the results of the bibliometric analysis revealed three distinct clusters of co-occurring keywords, each representing a set of closely related terms. Cluster 1 included words like "frailty," "fall prevention," "rehabilitation," and "balance," which are directly associated with physical function in old individuals. Cluster 2, on the other hand, contained keywords, including "sedentary behavior," "obesity," "diet," and "body composition." This suggests a focus of previous studies on the importance of lifestyle and habits in aging and PA research. Lastly, Cluster 3 consisted of terms, such as "depression," "dementia," "cognitive function," and "memory," demonstrating a research emphasis on the relationships among cognitive aspects, aging, and PA.

3.1.3. Trends in keywords by time

To classify research trends by era, keywords were grouped by decades (1991-2000 vs. 2001-2010 vs. 2011-2023). It was observed that 562, 1,720, and 10,919 manuscripts were published in the first, second, and third decades, respectively, which also supports the finding that the number of publications on this research topics has gradually increased.

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Table 1. Top 30 co-occurring keywords with aging and physical activity by decade.

	1991-2000			**2001-2010**			2011-08.2023		
	Keyword	**Occurrences**	**Total Link Strength**	**Keyword**	**Occurrences**	Total Link Strength	Keyword	Occurrences	Total Link Strength
1	body composition	29	77	body composition	50	145	sedentary behavior	485	1290
2	female	25	68	health promotion	58	136	obesity	447	1225
3	physical fitness	24	68	rehabilitation	48	116	quality of life	443	1108
4	middle age	23	57	quality of life	41	115	frailty	424	1126
5	activities of daily living	19	56	female	46	113	accelerometry	356	951
6	bone density	19	51	frailty	43	103	cognition	329	899
7	gender	19	47	physical fitness	42	98	health promotion	326	902
8	skeletal muscle	23	45	depression	33	96	fall prevention	311	820
9	health promotion	15	45	obesity	31	92	physical fitness	283	760
10	bone disease	15	43	skeletal muscle	40	91	diet	279	807
11	smoking	13	43	gender	38	90	body composition	265	668
12	heart rate	15	38	fall prevention	37	90	sarcopenia	260	719
13	vo_2max	15	35	balance	33	83	physical function	256	688
14	cardiovascular disease	11	35	disability	29	82	depression	253	653
15	risk factor	10	35	diet	26	81	rehabilitation	252	619
16	diet	13	31	smoking	23	75	skeletal muscle	245	602
17	blood pressure	11	31	middle age	33	70	nutrition	228	666
18	coronary disease	11	28	mobility	20	68	walking	227	607
19	longitudinal study	8	27	activities of daily living	33	67	female	223	520
20	mortality	8	27	walking	27	64	diabetes	212	523
21	male	8	24	muscle strength	26	62	muscle strength	203	524
22	physical performance test	16	23	physical function	26	59	balance	192	500
23	mice	12	23	nutrition	19	58	middle age	182	360
24	muscle strength	8	23	oxidative stress	23	51	healthy aging	178	400
25	leisure activity	8	21	cognition	20	50	lifestyle	176	546
26	self-efficacy	8	17	lifestyle	18	50	sleep	166	445
27	frailty	7	17	sarcopenia	21	47	digital health	157	471
28	walking	7	16	self-efficacy	17	47	behavior change	156	412
29	questionnaire	7	16	diabetes	17	46	adolescent	152	369
30	rehabilitation	7	13	prevention	16	43	activities of daily living	143	392

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Table 1 shows the top 30 keywords that appeared most frequently with the two searched keywords for each decade. The number of occurrences and their total link strength with other keywords were calculated for all keywords. In the first decade, keywords, "body composition," "activities of daily living," "health promotion," and "smoking," are noticed, suggesting that the effect of aging and PA on lifestyle and daily living were the primary focus of research during this period. In addition, the keywords, "female" and "gender" are highly ranked, suggesting that the gender differences in aging and PA were also a highlighted topic during the period. The frequently co-occurring keywords in the second decade were similar to those in the first decade. Of note, the keywords associated with diseases, such as "frailty," "depression," "sarcopenia," and "cognition" began to appear in earnest during this period. Notably in the past decade, the keyword, "sedentary behavior", appeared most frequently. The appearance of the disease-associated keywords mentioned above has also increased. Therefore, we selected "frailty" for the meta-analysis (the second aim) to comprehensively evaluate the efficiency of PA on frailty, which was revealed by bibliometric analysis to be significantly increasing in recent years.

Figure 5 shows the most co-occurring keywords and their distinct relationships in documents further by decade. It was found that co-occurring keywords became more diverse recently, and the number of appearance of specific keyword also increased significantly, in line with the findings shown in Figure 3. A network map for the first decade composed of "body composition", "heart rate" and "physical performance test" suggests that the measures of body and fitness in the older people and the effects of PA on them were actively examined during the first decade (Figure 5A). Consisting of newly appearing keywords, "rehabilitation," "physical fitness," and "disability," the network for the second decade (Figure 5B) demonstrates that PA began to be considered for its therapeutic role in improving physical function in the older people during the period. Over the last decade, network maps have consisted of three keyword groups. One is a network (red) formed with "sedentary behavior," "obesity," and "diet," etc., which suggests that the focus of research includes the associations of aging and PA with lifestyle and diet. Another part, a network consisting of "proteins," "skeletal muscle," and "sarcopenia," suggests a focus on the biology and function of skeletal muscle in the context of aging and PA. The network consisting of other parts, such as "frailty," "cognition," "rehabilitation," and "fall prevention," shows that improvement of physical and cognitive frailty of the older people through PA and improvement of quality of life are also hot topics recently (Figure 5C).

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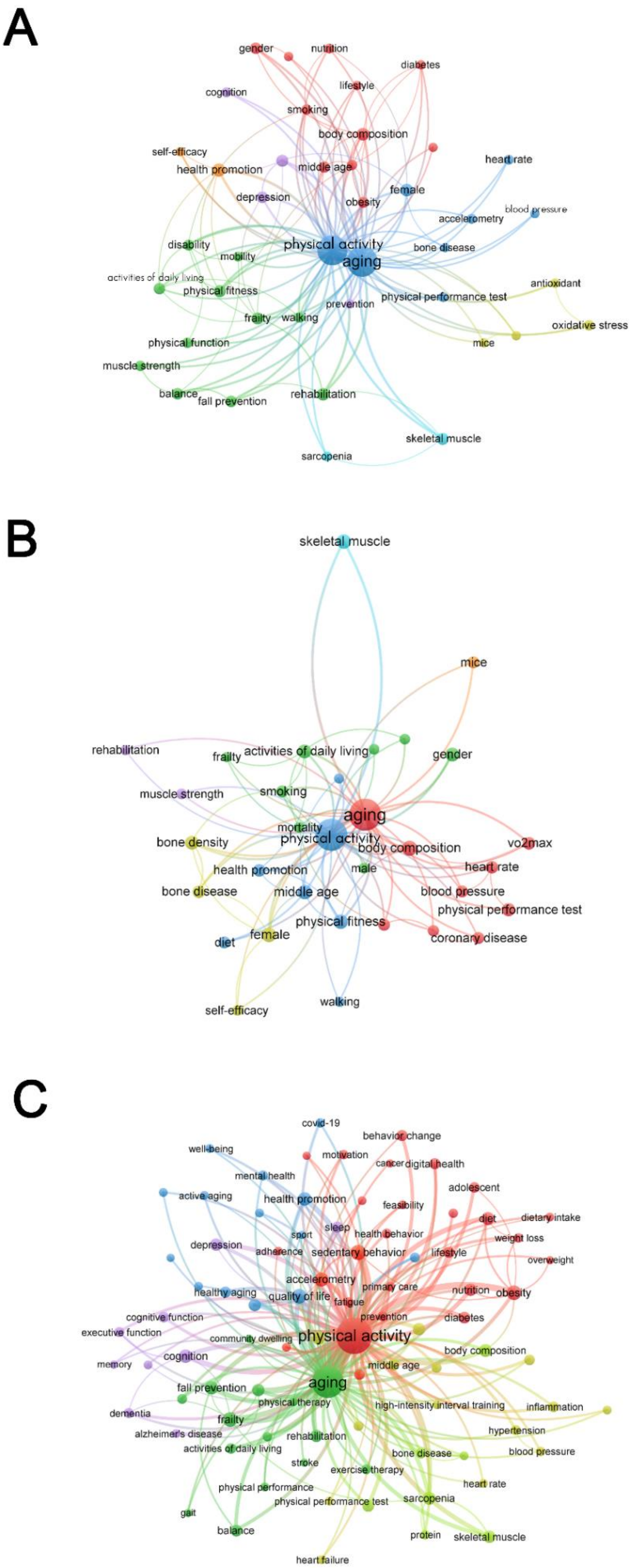

Figure 5. The keyword network from original articles having two keywords, 'aging' and 'physical activity' published between January 1991 and July 2023 is classified by decade. The keyword network from original articles published between A. January 1991 and December 2000 (appeared ≥ 7 times), B. January 2001 and December 2010 (appeared ≥ 15 times), C. January 2011 and July 2023 (appeared ≥ 60 times). The similarity between two keywords is proportional to the number of simultaneous occurrences, placing words with high similarity close together. The size of the circles representing keywords increases with the relevance of these keywords (total link strength), and the distinctive colors of the circles and lines mean the difference in modularity.

3.2. Meta-analysis

3.2.1. Quality check

PEDro scores ranged from 4 to 8 points, with a mean score of 5.56 (± 1.29). All studies fulfilled the following four criteria: random allocation, groups similar at baseline, between-group differences reported, and point estimates and variability reported. Some studies scored the criteria for assessor blinding as <15% dropout and intention-to-treat analyses. None of the studies met the criteria for participant or therapist blinding. The methodological qualities of the included studies are presented in Table 2.

Table 2. Physiotherapy Evidence Database (PEDro) scale of the included studies for meta-analysis.

Study	Eligibility criteria	Random allocation	Concealed allocation	Groups Similar at Baseline	Blinding of participants	Blinding of therapists	Blinding of assessors	Adequate follow-up (<15% Dropouts)	Intention-to-treat analysis	Between-group comparisons	Point estimates and variability	PEDro Score (0–10)
Fiatarone et al. 1994	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	7
Chandler et al. 1998	Y	Y	N	Y	N	N	Y	Y	N	Y	Y	6
Binder et al. 2002	Y	Y	N	Y	N	N	Y	N	N	Y	Y	5
Seynnes et al.2004	Y	Y	N	Y	N	N	N	N	N	Y	Y	4
Binder et al. 2005	Y	Y	N	Y	N	N	N	N	N	Y	Y	4
Boshuizen et al. 2005	Y	Y	N	Y	N	N	N	N	N	Y	Y	4
Giné-Garriga et al. 2010	Y	Y	Y	Y	N	N	Y	N	N	Y	Y	6
Zech et al. 2012	Y	Y	Y	Y	N	N	Y	Y	N	Y	Y	7
Ng et al. 2015	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y	8
Cadore et al. 2014	Y	Y	Y	Y	N	N	Y	N	N	Y	Y	6

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Serra-Prat et al. 2017	Y	Y	Y	Y	N	N	N	N	N	Y	Y	5
Yoon et al. 2017	Y	Y	N	Y	N	N	N	N	N	Y	Y	4
Sahin et al. 2018	Y	Y	N	Y	N	N	N	N	N	Y	Y	4
Vikberg et al. 2019	Y	Y	Y	Y	N	N	Y	Y	N	Y	Y	7
Chen et al. 2020	Y	Y	Y	Y	N	N	Y	Y	N	Y	Y	7
Barrachina et al. 2021	Y	Y	N	Y	N	N	N	Y	N	Y	Y	5
Barrachina-Igual et al. 2022	Y	Y	N	Y	N	N	Y	N	N	Y	Y	5
Swales et al. 2022	Y	Y	N	Y	N	N	N	Y	Y	Y	Y	6

N, no, do not meet the criteria; Y, yes, meet the criteria; Eligibility criteria item does not contribute to the total score.

3.2.2. Study characteristics

The characteristics of the 16 included studies are summarized in Table 3. The total sample size of all included studies was 1,160 participants with sample size ranging from 22 to 115 participants, including 638 in the PA intervention group (55%) and 522 in the control group (45%). The mean age of the participants was between 70.0 (± 4.7) to 93.4 (± 3.2) years, and 630 were female (54%). Most studies divided participants into a control group that performed routine daily activities (n= 11 studies), although five studies provided the control group with flexibility training. Resistance training (RT) was administered to the experimental group and mostly combined with other types of training, such as aerobic exercise, balance, gait, mobility, and flexibility training. The mean duration of the RT programs was approximately 10-12 weeks (range 8–36 weeks), and the most common training frequency was 2–3 times per week. The outcomes included one or more of the following measurements: handgrip strength, knee extensor strength, gait speed, timed up and go test (TUG), and short physical performance battery test (SPPB).

Table 3. Characteristics of the included studies for meta-analysis.

Study (Year, Country)	**N (IG/CG)**	**Age (years)**	**Gender (M/F)**	**Duration (Frequency)**	**Intervention**	**CG**
Fiatarone et al. 1994 (USA)	51 (25/26)	IG 86.2±5.0 CG 89.2±4.0	21/30	10 (3x/week)	**Progressive lower extremity RT** - Hip and knee extensors (80% of 1-RM)	-
Chandler et al. 1998 (USA)	100 (50/50)	77.6±7.6	50/50	10 (3x/week)	**Progressive lower extremity RT** - Resisted hip extension and abduction, knee flexion and extension, ankle dorsiflexion, toe raises, chair rises, and stair stepping (2 set x 10 rep) - Once the participant could perform two sets of 10 easily at a given color of theraband, the resistance was increased	No resistance training was allowed, but aerobic or flexibility exercises were permitted

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					by replacing the theraband with the next color	
Binder et al. 2002 (USA)	115 (66/49)	IG 83.0±4.0 CG 83.0 ± 4.0	55/60	36 (2-3x/week)	**Three approximately 3-month-long phases of ET** - Phase 1: 22 exercises that focused on improving flexibility, balance, coordination, speed of reaction and, to a modest extent, strength - Phase 2: Progressive RT (1-2 set x 6-8 rep, 65 % of 1-RM) - Phase 3: Endurance training 15-20min (65-75% of VO2peak) - Shortened programs of Phase 1 and Phase 2 exercises were continued during Phase 3	Home-based exercise program focused primarily on flexibility (60min, 2-3x/week) was performed
Seynnes et al. 2004 (France)	22 (HI 8/ LI 6/ CG 8)	81.5	N/A	10 (3x/week)	**Progressive lower extremity RT** - Knee extensor muscles - HI: 3 set x 8 rep, 80% of 1-RM - LI: 3 set x 8 rep, 40% of 1-RM	-
Binder et al. 2005 (USA)	91 (53/38)	83.0±4.0	42/49	36 (3x/week)	**Multi-component exercise program** - 1-12weeks: Light-resistance + flexibility + balance training - 13-24week: Resistance + Flexibility + balance training - 25-36week: Resistance + Flexibility + balance + endurance training	Home-based exercise program focused primarily on flexibility (60min, 2-3x/week) was performed
Boshuizen et al. 2005 (Netherlands)	72 (HG 24/MG 26/CG 22)	HG 80.0±6.7 MG 79.3±7.0 CG 77.2±6.5	4/68	10 (3x/week)	**Lower extremity RT** - HG: 2 group sessions + 1 home session - MG: 1 group session + 2 home session	-
Giné-Garriga et al. 2010 (Spain)	51 (26/25)	84.0±2.9	20/31	12 (2x/week)	**Progressive lower extremity RT + balance training** - 1 day of balance-based activities and 1 day of lower body strength-based exercises (RPE intensity of 12–14; 1-2set x 6-8 rep)	-
Zech et al. 2012 (Germany)	69 (ST 23/ PT 24/ CG 22)	ST 77.8±6.1 PT 77.4±6.2 CG 75.9±7.8	N/A	12 (2x/week)	**Progressive RT + Balance training** - ST: with an 'average' velocity (2–3 s) - PT: move as rapidly as possible during the concentric phase of each repetition and to move slowly during the eccentric phase (2–3 s)	-
Cadore et al. 2014 (Spain)	24 (11/13)	IG 93.4±3.2 CG 90.1±1.1	7/14	12 (2x/week)	**Multi-component exercise program** - Upper and lower body RT with progressively increased loads (1 x 8-10 rep, 40-60% of 1-RM) with balance and gait retraining	Mobility exercises were performed 30min per day (4x/week)
Ng et al. 2015 (Singapore)	98 (48/50)	70.0±4.7	43/55	24 (2x/week)	**Progressive RT + functional tasks + balance training** - 1-12 weeks: classes conducted by a qualified trainer - 13-24 weeks: home-based exercises	-
Serra-Prat et al. 2017 (Spain)	172 (80/92)	IG 77.9±5.0 CG 78.8±4.9	75/97	48 (4x/week)	**Multi-component exercise program** - Aerobic exercise: walking outdoors for 30-45min	-

					- Strengthening arms, legs, and balance training for 20-25 min	
Yoon et al. 2017 (Korea)	58 (HSPT 19/ LSST 19/ CG 20)	HSPT 75.0±0.9 LSST 76.0±1.3 CG 78.0±1.0	0/58	12 (2x/week)	**Progressive RT with elastic bands** - HSPT: Low-intensity, 2-3 set x 12-15 rep - LSST: High-intensity, 2-3 set x 8-10 rep	Static and dynamic stretching exercises (60min, 1x/week) were performed
Sahin et al. 2018 (Turkey)	48 (HI 16/ LI 16/ CG 16)	HI 84.2±6.9 LI 84.5± 4.8 CG 85.4±4.7	N/A	8 (3x/week)	**Whole body RT** - HI: 1 set x 6-10 rep, 70% of 1-RM - LI: 1 set x 6-10 rep, 40% of 1-RM	-
Vikberg et al. 2019 (Sweden)	70 (36/34)	70.9±0.03	32/38	10 (3x/week)	**Whole body RT, with a focus on strengthening of the lower-extremity** - Moderate to high RT intensity was applied using the Borg CR-10 scale (6-7/10) - 1week: 2set x 12 rep - 2-4 weeks: 3set x 10 rep - 5-7 weeks: 4set x 10 rep - 8-10 weeks: 4set x 10 rep	-
Chen et al. 2020 (China)	70 (35/35)	IG 77.0±5.2 CG 75.3±6.0	23/43	8 (3x/week)	**Whole body RT with elastic bands** - 2 set x 10-15 rep	-
Barrachina-Igual et al. 2021 (Spain)	50 (27/23)	75.0±7.0	13/37	12 (2x/week)	**Multi-component exercise program** - Balance, flexibility, aerobic (10min warming-up) and progressive RT (3set x 10-15 rep, 70% of 1-RM) combined with self-massage for myofascial release	-
Swales et al. 2022 (UK)	11 (6/5)	86.1±7.2	4/7	6 (3x/week)	**RT** - Warm-up for 5min - Resistance training: optimal rhomboid, hip adduction, hip abduction, chest press, leg extension, leg curl, leg press (2 set x 12 rep)	-
Barrachina-Igual et al. 2022 (Spain)	81 (39/42)	77.6±7.5	13/68	20 (2x/week)	**Multi-component exercise program** - Warm-up exercise: aerobic exercise and joint mobility for 10 min - Progressive high intensity RT: 6 strength exercise (2 trunk, 2 arms and 2 legs) 3 set x 8-12 rep for 42-45 min - Self-massage for myofascial release: 7 exercise per session (4 lower limb, 1 chest and 2 back) 1set x 10 rep for 9-10 min	Continue their routine daily activities

IG, intervention group; CG, control group; M, male; F, female; RT, resistance training, RM, repetition maximum; HG, high guidance group; MG, medium guidance group; RPE, rating of perceived exertion; ST, strength training; PT, power training; HSPT, high-speed power training; LSST, low-speed strength training; HI, high intensity resistance training; LI, low intensity resistance training. Data for age are mean±standard deviation.

3.2.3. Body Composition

Eight trials involving 452 participants provided post-intervention data on body mass index (BMI) (Figure 6A). There was a significant improvement in BMI compared with the control with an effect size (ES) of -1.031 [95%confidence interval (CI): -1.230 to -0.831; $p<0.001$]. Fourteen studies provided data on muscle masses from 779 participants (Figure 6B), showing a significant change with RT (ES=0.345, 95% CI= 0.114 to 0.576, $p<0.01$). Subgroup analyses were further performed, and significant RT effects in total muscle mass (ES= 0.349, 95% CI= 0.035 to 0.663, $p<0.05$, I^2 = 53%) was found, but not in appendicular muscle mass (ES= 0.336, 95% CI= -0.038 to 0.711, p=0.07, I^2 = 67%). The heterogeneity of the results regarding body composition outcomes was very low for body mass index (I^2 = 0%) and moderate for muscle mass (I^2 = 57%).

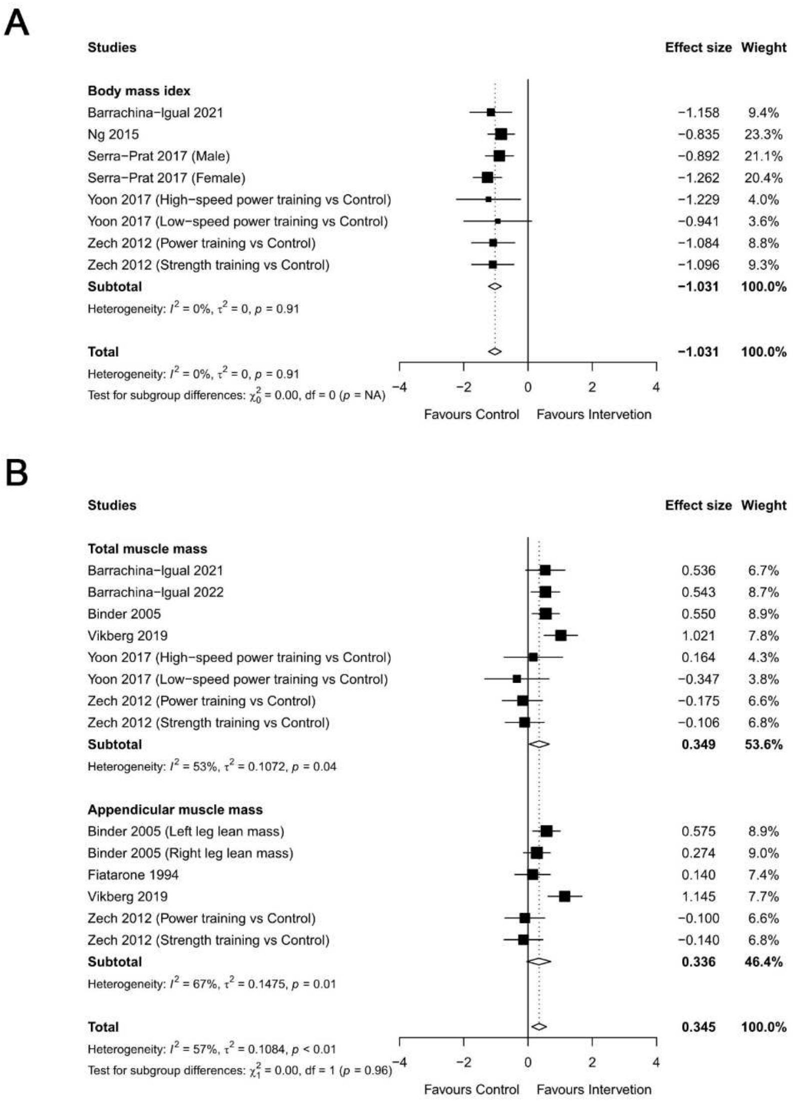

Figure 6. Overall meta-analysis findings and forest plot showing the comparative effect of resistance training versus control group on the body composition (A. Body mass index and B. Muscle mass) in frail elderly people. Diamonds demonstrate overall effect sizes. Effect size smaller than zero favors resistance training for body mass index. Effect size greater than zero favors resistance training for muscle mass.

3.2.4. Muscular Strength

Eleven trials, including 548 participants, provided post-intervention data on handgrip strength (Figure 7A). The results demonstrate a significant difference in handgrip strength between the training group and control groups (ES=0.915, 95% CI= 0.334 to 1.500, p<0.01). For lower-limb strength (isometric knee extension and isokinetic knee flexion), 28 studies including 1,215 participants were found (Figure 7B). The meta-analysis showed significant changes in lower-limb strength (ES= 0.761, 95%CI= 0.486 to 1.04, p<0.001) in the RT group. Sub-measurement analyses were performed for lower-limb strength, and significant changes in both isometric knee extension (ES= 0.672, 95% CI= 0.527 to 0.818, p<0.001, I^2 = 74.7%) and isokinetic knee flexion (ES= 0.443, 95% CI= 0.239 to 0.647, p<0.001, I^2 =

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26.5%) were found. The heterogeneity of the outcomes was high for handgrip strength ($I^2 = 86\%$) and moderate for lower-limb strength ($I^2 = 68\%$).

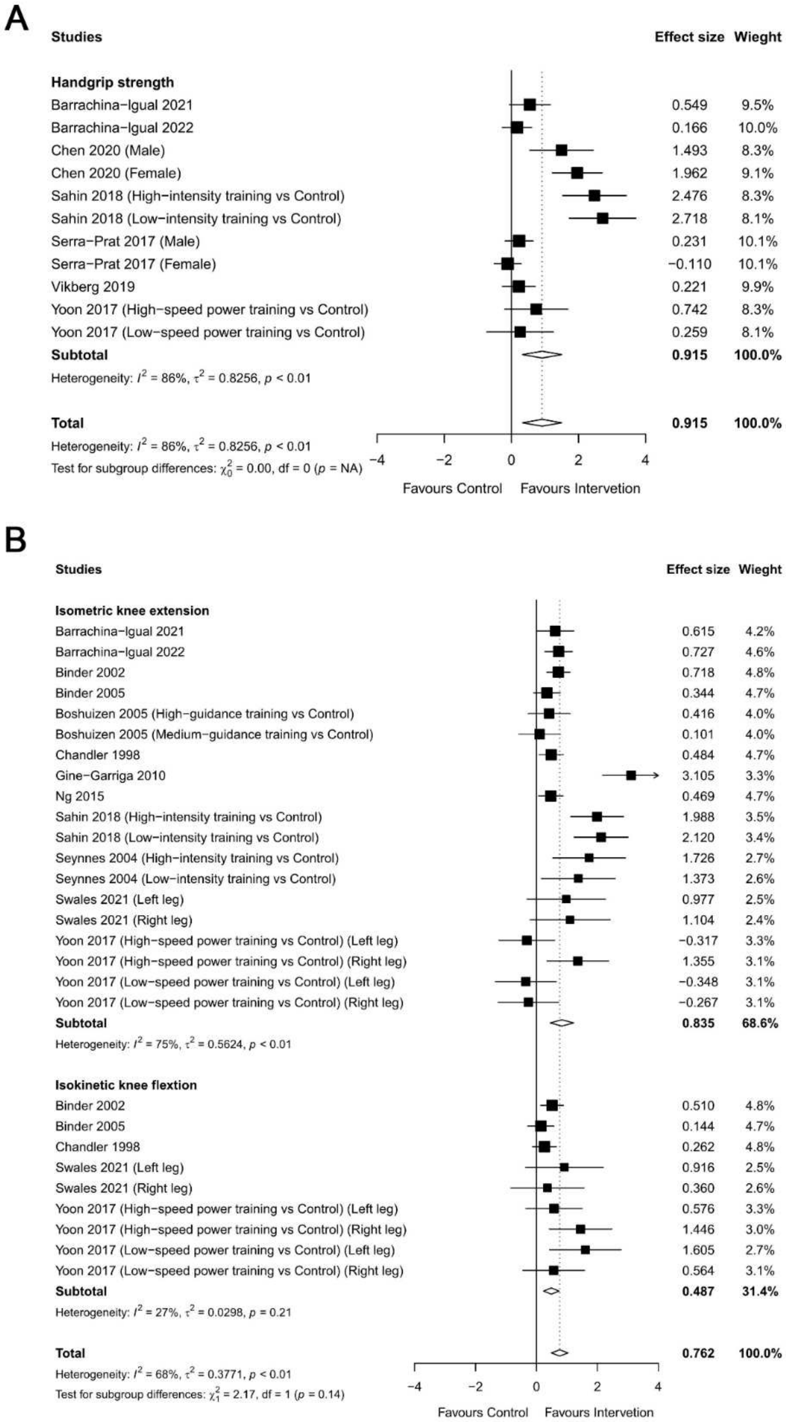

Figure 7. Overall meta-analysis findings and forest plot showing the comparative effect of resistance training versus control group on the muscular strength (A. Handgrip strength and B. Lower-limb strength) in frail elderly people. Diamonds demonstrate overall effect sizes. Effect size greater than zero favors resistance training.

3.2.5. Physical Function

The effects of RT have been reported for balance in 15 studies (681 participants), gait speed in 14 studies (667 participants), and agility (TUG) in eight studies (366 participants). Meta-analysis found

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significant changes in favor of RT group for the balance (ES= 0.849, 95% CI= 0.093 to 1.61, $p < 0.05$) (Figure 8A), and gait speed (ES= 1.101, 95% CI= 0.357 to 1.85, $p<0.05$) (Figure 8B). But there was no significant effect in agility (ES= 0.657, 95 %CI= -0.107 to 1.422, p=0.092) (Figure 8C). Sub-measurement analyses for balance yielded a positive significant effect on one-leg standing time (ES= 1.448, 95% CI = -0.529 to 3.425, $p<0.01$, $I^2 = 90\%$) and the SPPB balance test (ES= 0.432, 95% CI = 0.219 to 0.646, $p<0.001$, $I^2 = 0\%$). The heterogeneity of the results around these outcomes was moderate for balance ($I^2 = 60.5\%$), and high for gait speed ($I^2 = 83.6\%$), and agility ($I^2 = 84.1\%$).

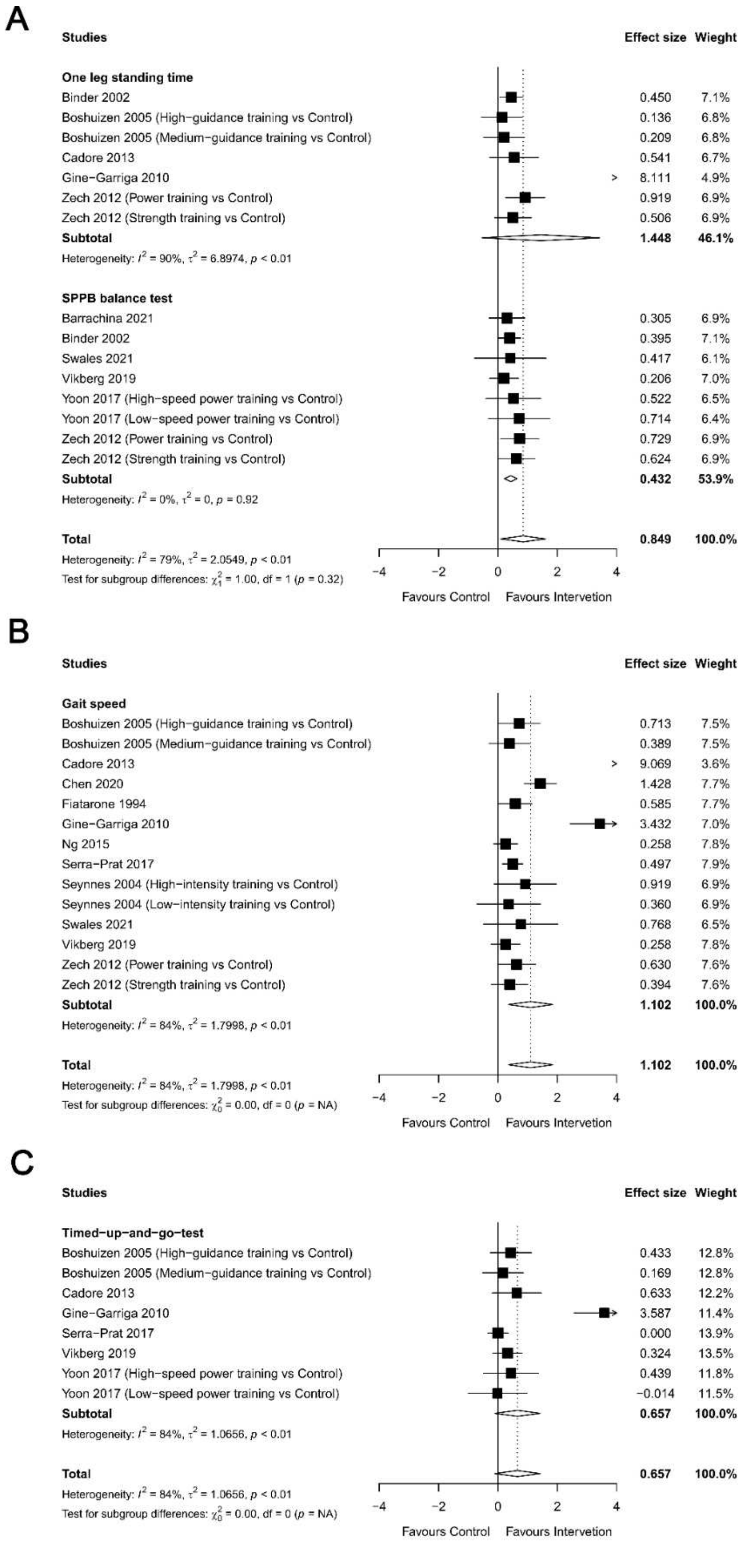

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Figure 8. Overall meta-analysis findings and forest plot showing the comparative effect of resistance training versus control group on the physical function {A. Balance [one leg standing, short physical performance batter (SPPB)], B. Gait speed, and C. Timed-Up-and-Go-test (TUG)} in frail elderly people. Diamonds demonstrate overall effect sizes. Effect size greater than zero favors resistance training.

3.2.6. Functional Strength

Seven trials involving 176 participants provided post-intervention data on functional strength (Figure 9). There was not a significant improvement in functional strength compared to the control after pooling the results (ES= 0.973, 95% CI= -0.311 to 2.256, p=0.09). As a result of the sub-measurement analyses, chair stand test results, reported in four studies (95 participants), did not change with RT (ES= 1.163, 95% CI= -1.260 to 3.585, p=0.32). A significant change was observed in the stair-climbing tests (ES= 0.870, 95% CI= 0.410 to 1.330, p<0.001). The heterogeneity of the results around the outcomes was high for the total functional strength (I^2 = 90%) and chair stand test (I^2 = 95%), but very low for the stair climbing test (I^2 = 0%).

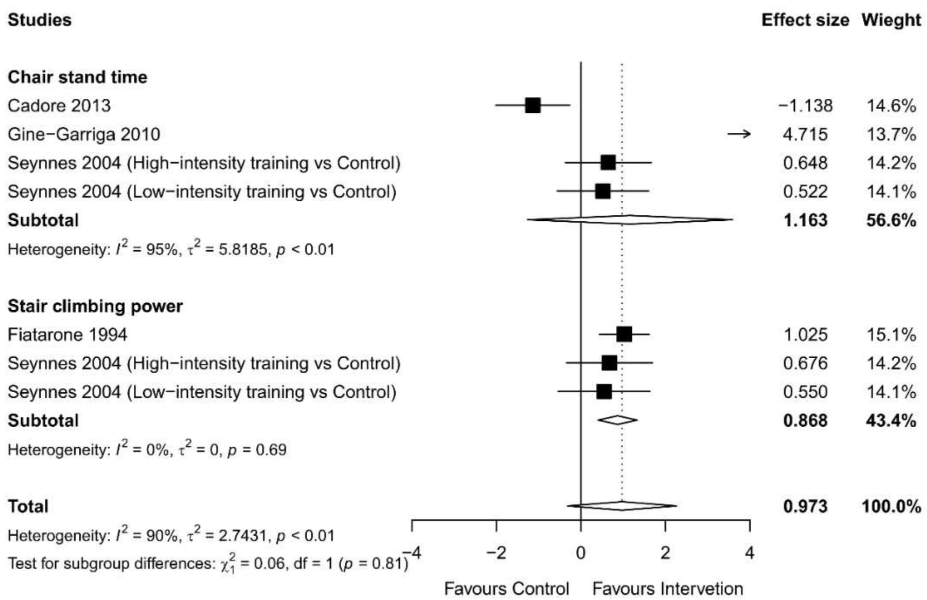

Figure 9. Overall meta-analysis findings and forest plot showing the comparative effect of resistance training versus control group on the functional strength (chair stand and stair climbing) in frail elderly people. Diamonds demonstrate overall effect sizes. Effect size greater than zero favors resistance training.

4. Discussion

By 2050, the number of older adults is expected to almost double to 2.1 billion due to increases in life expectancy [45]. Nevertheless, increase in life expectancy may not convert into increase in lifespan without disability, and these individuals may experience poor general health during their prolonged years [7]. Therefore, maintaining the physical health of older adults is a critical public health concern. Accumulating evidence indicates that PA is a highly effective non-therapeutic approach for promoting healthy aging [12,13]. PA can improve functional capabilities and mitigate physical comorbidities associated with aging [14], directly contributing to the quality of life. Therefore, efforts to elucidate the roles of PA in successful aging have accumulated over the past few decades [17]. However, there have been no attempts to identify the large volumes and growth patterns of accumulated data affecting the development of aging and PA research, and no bibliometric analysis has examined the connection between them. Accordingly, the first aim of this study was to review the literature published on aging and PA research using bibliometric analysis in order to illustrate the research landscape and identify hot topics and emerging trends in aging and PA research.

The results of the bibliometric analysis show that a handful of publications between the 1990s and the 2000s have increased to a substantial research field in recent years. This trend reflects the growing interest of institutions and researchers in aging and PA, highlighting their essential roles in human disease, health, and lifespan. Our findings from the author keyword visualization map demonstrate that overall, co-occurring keywords with aging and PA can be categorized into three subject categories: 1) physical function and rehabilitation, 2) lifestyle factors, and 3) cognitive function. The classified research trend by era further indicate that while studies from the early (1990s) to mid-term (2000s) periods mainly looked at the relationship between lifestyle factors, aging, and PA, more recently, studies have been conducted with a focus on specific aging-associated diseases, such as frailty, sarcopenia, and depression. These findings provide a guide for future studies exploring the mechanisms by which aging contributes to these diseases and how PA can prevent or ameliorate the effects of aging.

Bibliometric analysis revealed "frailty" as the fastest growing research keyword in the fields of aging and PA research. This is consistent with recent studies highlighting that frailty affects an estimated 11% of older adults [46] and is the most common condition influencing older adults in terms of both mortality and morbidity [47]. Furthermore, the recent generations of older adults tend to have higher frailty levels [48]. Therefore, the second aim of this study was to investigate the effects of RT, the recommended PA type for the older people [22], on frail older individuals via a meta-analysis of the literature that studied the effects of RT on body composition, muscular strength, and physical function in frail older adults. The results of this meta-analysis provide evidence that RT is effective in lowering BMI, increasing muscle mass, and improving muscle strength, balance, and walking speed. Our study is not only the first to apply bibliometric analysis to aging and PA research, but also the first to logically verify the effect of PA (RT) through a meta-analysis targeting the main keywords found through bibliometric analysis.

The results of this meta-analysis demonstrated that reducing BMI could potentially improve frailty. This is in line with previous findings that overweight and obese states based on BMI are associated with a higher frailty risk [49]. However, it is also noticeable that BMI does not directly indicate body composition such as adiposity which becomes more pronounced with age and is associated with progression to sarcopenic obesity [50,51]. Additionally, women may be more susceptible to frailty due to their higher intrinsic adiposity [52], and older women are more likely to experience obesity-related frailty [53]. Thus, it is important to acknowledge the limitations of associating BMI with total frailty across sexes.

A result of this meta-analysis revealed a significant increase in muscle mass in response to RT in frail older adults. A reduction in lean body mass with an accompanying increase in fat mass is one of the most striking and consistent changes observed with aging [3]. Low muscle mass is considered an inevitable condition and key component of physical frailty [54]. Increasing muscle mass in older adults can be challenging because age-related changes in hormonal profiles and physiological functions can hinder muscle protein synthesis [55]. However, studies have shown that RT can effectively increase muscle mass in older adults. This beneficial effect of RT on muscle mass has also been observed in individuals with other health conditions and functional limitations [56]. In addition, these positive changes in body composition parameters with RT can reduce the risk of other common diseases, such as metabolic syndrome and diabetes in older adults [57]. Muscular strength, which is directly related to muscle mass, is a crucial component of physical function and associated with various health outcomes in older adults [58]. Hand grip and leg strength tests are widely used to measure muscle strength [59]. We assessed the effects of RT on these two measures. Handgrip strength is often used as an indicator of overall muscle strength in aging adults and physical function in older adults, and low handgrip strength is associated with a variety of poor health outcomes, including chronic morbidities, functional disabilities, and all-cause mortality [60]. Similarly, lower-limb strength is critical for maintaining mobility and independence in older adults [61]. In line with previous studies, our results demonstrate that RT has a significant positive effect on both handgrip strength and lower-limb strength, indicating that RT helps enhance or preserve muscular strength and thus prevents or ameliorates frailty.

Mobility loss is particularly burdensome because of its strong association with negative health outcomes, loss of independence and disability, and its heavy impact on the quality of life [62]. Older adults show age-related declines in balance and gait with increased gait variability and an associated increase in the risk of falls [63]. These are particularly important given the importance of measures for fall prevention and overall mobility in older adults [64]. Our results demonstrate that RT is an effective way to improve balance and gait speed, which has implications for maintaining independence and quality of life in older adults. The TUG test has been extensively used to assess balance and mobility simultaneously in older adults [65–67], and previous studies have shown that RT improves TUG test scores in healthy older adults [68]. However, our meta-analysis found no significant effect of RT on TUG test scores. This could be due to the small number of studies (n=8) and/or heterogeneity of the RT program, suggesting that future studies should investigate the effects of RT on the TUG test in older adults. In addition, our findings indicated that RT had no significant effect on chair stand time. One possible explanation could be the high heterogeneity observed in the trials as indicated by the high standard deviation (Tau2= 5.82) and small number of studies (n=4). Future studies examining the effects of RT on the chair-stand test in frail older adults are warranted to confirm the results of previous studies. In contrast, a significant improvement in stair climbing was observed among individuals who participated in the RT programs. This finding is consistent with previous studies showing that RT can improve lower-limb muscle power, which is critical for tasks such as stair climbing [69].

5. Conclusions

Our study is the first to analyze research trends in aging and PA studies using bibliometric analysis with an additional meta-analysis with focus on frailty, which was noticed as the most popular co-occurring keyword with aging and PA. Bibliometric analysis has revealed that the number of publications on this research topic has increased steadily from the 1990s to the present, indicating a growing interest in understanding the role of PA in aging and its importance in human health. Frailty was found to be the most noteworthy keyword co-occurring with aging and PA. Thus, we further investigated the effects of RT on frail older adults. Meta-analysis found that RT had significant positive effects on physical factors associated with frailty, including handgrip strength, lower-limb strength, balance, gait speed, and stair climbing ability in frail older individuals except for the TUG or chair stand tests. These findings indicate that RT is an effective intervention for improving physical function among frail older adults, particularly for tasks that require lower-limb muscle power.

Given that the global population is aging, the results of bibliometric analysis indicate that PA as an anti-aging approach has become a field of great interest. In particular, our meta-analysis findings have important implications for the development of PA programs that can help older adults maintain their independence and quality of life by alleviating physical frailty. Future research should investigate the optimal dose, frequency, and duration of RT programs for older adults, as well as the potential benefits of combining RT with other forms of PA, such as aerobic or balance exercises.

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