Chen
Journal of Health, Population and Nutrition (2025) 44:272
https://doi.org/10.1186/s41043-025-01031-w

Journal of Health, Population and Nutrition

REVIEW

Open Access

Nutritional interventions in muscle hypertrophy research: a scientometric analysis within the context of resistance training (1992–2025)

Wei Chen[1,2*]

Abstract

Background Muscle hypertrophy, as a central goal in sports training, rehabilitation interventions, and health promotion, relies on scientifically designed resistance training and appropriate nutritional strategies. However, research on the synergistic effects of nutritional interventions and resistance training in promoting muscle hypertrophy is characterized by thematic fragmentation, insufficient integration between mechanistic and applied research, and imbalances across different regions and population groups.

Methods To systematically delineate the developmental trajectory and emerging trends in this field, a comprehensive search was conducted in the Web of Science Core Collection, initially retrieving 456 publications. After rigorous screening and data cleaning, 411 English-language articles published between 1992 and 2025 were retained for analysis. Scientometric techniques were applied to construct knowledge maps using three major tools: Bibliometrix (R 4.4.3), VOSviewer (1.6.20), and CiteSpace (6.2.6). Bibliometrix was used to analyze publication trends and thematic evolution; VOSviewer to map keyword co-occurrence and collaboration networks; and CiteSpace to detect citation bursts and visualize knowledge structures. Collectively, these methods facilitated the identification of high-frequency keywords, hotspot transitions, collaborative patterns, and underexplored thematic gaps.

Results The results indicate that: (1) the combination of protein supplementation and resistance training represents the most prominent intervention strategy; (2) a stable tripartite research model has emerged, centering on the interaction among training, nutrition, and structural adaptation; (3) the thematic focus has gradually shifted from molecular mechanisms toward practical applications, emphasizing issues such as aging and functional improvement; and (4) notable research gaps remain, particularly the underrepresentation of women and Asian populations, insufficient attention to recovery, metabolism, and periodized nutrition, and the lack of a systematic framework for individualized interventions.

Conclusion This study delineates the developmental trajectory, structural characteristics, and future directions of research in this field over the past three decades, providing empirical evidence and a theoretical foundation for the scientific formulation of muscle health enhancement strategies.

Keywords Muscle hypertrophy, Nutritional, Interventions, Resistance training, Scientometric analysis, Knowledge mapping, Co-citation network

*Correspondence:
Wei Chen
wei-1991@graduate.utm.my
Full list of author information is available at the end of the article

Introduction

Muscle hypertrophy is not only a crucial physiological foundation for improving athletic performance but also plays a key role in preventing age-related sarcopenia, improving metabolic health, and addressing chronic diseases [1–3]. Research on muscle hypertrophy has been widely applied in various fields such as sports science [4], nutrition [5], and rehabilitation medicine [6]. The findings of these studies hold significant practical implications for athletes, fitness enthusiasts, and clinical populations alike.

Among the primary strategies to promote muscle hypertrophy, nutritional interventions and resistance training are widely recognized as the two fundamental pillars. Nutritional strategies aim to enhance muscle protein synthesis (MPS) through targeted supplementation of key nutrients such as protein, amino acids, and creatine. Resistance training, on the other hand, stimulates structural and functional adaptations in muscle by imposing mechanical tension. In addition, recent studies have begun to explore the potential regulatory roles of micronutrients—such as vitamin D and vitamin B1—on muscle physiology under conditions of stress or metabolic dysfunction, thereby broadening the scope of nutritional intervention research to some extent [7, 8].

The issue of "thematic fragmentation" is primarily reflected in the disconnection and lack of integration among different research trajectories. For instance, one line of research focuses on the short-term effects of single nutrients—particularly the regulatory mechanisms of leucine in activating the mTORC1 pathway and promoting muscle protein synthesis (MPS), which have been extensively validated [9, 10]. In contrast, another body of literature emphasizes the long-term effects of resistance training variables—such as frequency and periodization—on muscle hypertrophy, suggesting potential synergistic effects between protein intake and training frequency [11]. These two strands of research often remain isolated in terms of study design, outcome indicators, and citation patterns, lacking a cross-variable integrative framework. This disconnect has contributed to persistent informational silos between nutrition- and training-focused studies. Furthermore, with the growing diversification of research topics—such as gut microbiota, anti-inflammatory nutrients, and sex-based differences [12, 13]—emerging themes have yet to establish synergistic linkages with the conventional "protein + resistance training" paradigm, thereby exacerbating internal thematic dispersion and structural imbalance within the field.

On the other hand, a notable disconnect persists between mechanistic research and applied intervention studies. While a substantial body of literature has focused on molecular mechanisms such as mTOR signaling and myostatin regulation [14], few studies have systematically translated these basic scientific findings into concrete intervention strategies—such as specific nutritional compositions or temporally optimized training regimens. As Thomas et al. [15] emphasized, muscle adaptation is a dynamic, spatiotemporal process, and single-variable studies are insufficient to elucidate its complexity. They advocate for integrative approaches that incorporate proteomics and longitudinal designs across multiple time points. In a randomized intervention trial, Bagheri et al. [16] reported that although various levels of protein intake significantly increased lean mass, they showed no significant correlation with functional outcomes such as strength, endurance, or power, highlighting a decoupling between structural improvement and functional gains. Additionally, Deane et al. [17] noted that simply increasing protein intake cannot overcome the “muscle saturation” plateau; progressive training stimuli remain essential for achieving meaningful hypertrophic adaptations.

Overall, mechanistic insights have not been adequately embedded into intervention research design, and most intervention studies lack the concurrent tracking of mechanistic biomarkers. This dual disjunction has created a structural barrier between theoretical mechanisms and practical applications, underscoring the urgent need to develop an integrated research paradigm that bridges layers and variables.

In response, this study employs a scientometric approach to systematically analyze literature from the Web of Science Core Collection published between 1992 and 2025, with the aim of constructing a comprehensive knowledge map of this interdisciplinary domain. Four specific research objectives were established:

> *Quantify the evolution of knowledge structures*—Analyze annual publication trends, burst keywords, and collaborative networks among countries, institutions, and authors to characterize the evolutionary trajectory from “mechanistic foundation” to “applied expansion” and ultimately “multimodal integration,” while mapping a “core–hub–periphery” pattern of knowledge diffusion.
>
> *Elucidate intervention pathways and mechanistic coupling*—Utilize a “nutrition × training” co-occurrence matrix and dual clustering of co-citation and co-word networks to validate the tripartite model of “protein/amino acids + resistance training + muscle outcomes,” while identifying research gaps in areas such as recovery, metabolic health, and periodized nutrition.

Identify population and regional disparities—Compare keyword and citation patterns across sex, age groups, and geographic regions to locate underrepresented populations—particularly women, older adults, and non-Western cohorts—and evaluate the implications for the generalizability and external validity of current evidence.

Propose an evidence-based research agenda—Based on structural gaps and emerging hotspots, provide actionable recommendations for future studies on precision nutrition and resistance training, including key design considerations, to support cross-cultural application and translational impact.

As a scientific methodology grounded in large-scale literature data, scientometric analysis enables researchers to systematically uncover the structural characteristics, evolutionary trajectories, and future potential of a given research field from a macro-level perspective, thereby providing empirical support for the development of more targeted research strategies [18, 19]. This approach is particularly valuable in interdisciplinary and conceptually layered domains—such as the present study on "nutritional interventions for promoting muscle hypertrophy"—where the integration of multiple tools, including Bibliometrix [20], VOSviewer [21], and CiteSpace [22], facilitates the construction of comprehensive knowledge maps and highlights emerging directions for future inquiry.

In recent years, some scholars have attempted to integrate systematic reviews with scientometric analysis to deepen content understanding and structural insight into specific research domains (e.g., Azizan et al. [23]). However, existing studies have primarily focused on sarcopenia-related interventions or isolated variables such as protein intake and training frequency, lacking a comprehensive, cross-disciplinary synthesis and structural examination of integrated themes.

In contrast, the present study is the first to incorporate the tripartite themes of "nutritional intervention × resistance training × muscle hypertrophy" within a unified analytical framework. By employing a combination of Bibliometrix, VOSviewer, and CiteSpace, we constructed a panoramic knowledge map that spans macro-level evolutionary patterns to micro-level mechanistic pathways. Furthermore, this study offers a critical structural diagnosis of the disjunctions between "protein-focused research and training interventions" and between "mechanistic exploration and practical strategies." It also identifies substantial gaps in the literature concerning underrepresented populations, such as women, older adults, and non-Western cohorts, and proposes an actionable research agenda aimed at precision nutrition and resistance training strategies tailored to these groups. Overall, this study demonstrates substantial innovation in thematic integration, methodological synthesis, and structural insight. It provides a robust foundation for future knowledge consolidation and the practical translation of research in the field of muscle hypertrophy.

Materials and methods

Data source and search strategy

This study conducted a comprehensive literature search using the Web of Science Core Collection (WoS CC) database, with the aim of systematically revealing the developmental trends and knowledge structures related to nutritional interventions in resistance training–induced muscle hypertrophy. The WoS CC is widely recognized as a high-quality and authoritative source of scientific literature [24], and has been extensively utilized in scientometric analyses [25]. To comprehensively assess the current research landscape and evolutionary trajectory within the domain of "muscle hypertrophy under nutritional intervention," a logically layered search strategy was constructed and executed in the WoS database on April 4, 2025.

To ensure the accuracy and rigor of the search strategy, a three-tiered Boolean logic structure was constructed, encompassing the following core thematic categories: (1) muscle hypertrophy and its related concepts, including "muscle hypertrophy," "muscle growth," and "muscle gain"; (2) nutritional interventions, such as "nutritional intervention," "protein supplementation," "amino acids," and "creatine"; (3) resistance training and its specific modalities, including "resistance training," "strength training," and "bodybuilding." The methodological design employed in this study aligns structurally with that of Azizan [26], who demonstrated a systematic approach to keyword refinement and co-word visualization in a scientometric analysis on sensor-assisted fall prevention. This parallel underscores the methodological rigor and logical coherence required for constructing scientific search strategies within health-related interdisciplinary domains.The full search query is as follows: TS = ("muscle hypertrophy" OR "skeletal muscle hypertrophy" OR "muscle growth" OR "muscle mass increase" OR "increased muscle mass" OR "muscle gain" OR "gain muscle" OR "muscle fiber hypertrophy") AND TS = ("nutrition" OR "nutritional strategy" OR "nutritional strategies" OR "nutritional intervention" OR "nutritional interventions" OR "dietary supplementation" OR "dietary protein" OR "protein intake" OR "protein supplementation" OR "amino acid supplementation" OR "essential amino acids" OR "leucine" OR "branched-chain amino acids" OR "whey protein" OR "casein" OR "creatine" OR "creatine supplementation" OR "creatine monohydrate" OR "nutrient timing" OR "post-exercise nutrition" OR "peri-workout nutrition" OR "high-protein diet") AND TS=("resistance training" OR "resistance exercise" OR "strength training" OR "strength exercise" OR "weight training" OR "weightlifting" OR "power training" OR "resistance-based exercise" OR "bodybuilding" OR "hypertrophy-oriented training").

It should be particularly noted that this study utilized the Web of Science–recommended Topic (TS) search field, encompassing article titles (TI), abstracts (AB), author keywords (AK), and Keywords Plus (KP), rather than relying solely on the Title (TI) field. This comprehensive approach ensures the systematic coverage and completeness of the literature search, significantly reducing the risk of omitting relevant publications due to narrower title-only searches. To further guarantee the scientific validity and thoroughness of the search strategy, two domain experts specializing in sports nutrition and resistance training were invited to independently review and validate the search logic and keyword combinations. Both experts confirmed that the search strategy was logically rigorous, comprehensive in keyword coverage, and reflective of the intended research theme (Appendix A).

Additionally, a systematic examination of initial search results indicated that the year 1992 marked the first intersection of the triple themes—nutritional interventions, muscle hypertrophy, and resistance training—in the Web of Science Core Collection, with four related publications identified (including both human interventions and animal experiments). Thus, the period from 1992 to 2025 was selected to ensure both foundational literature inclusion and academic continuity. This defined timespan aligns closely with recent trends in scientometric studies. For example, Azizan et al. [27], in their research on digital biomarkers, adopted a similarly extensive temporal scope spanning over two decades, integrating systematic scope assessment with scientometric methods to chart the research evolution. Analogously, the current study employed a 33-year analysis window to comprehensively cover foundational works and emerging hotspots in this interdisciplinary field, thereby ensuring analytical timeliness and continuity.

The literature search was conducted on April 4, 2025, initially identifying 456 articles. After excluding non-article/review documents (n=9), records not indexed in SCI/SSCI journals (n=28), and non-English publications (n=6), a total of 413 articles met the inclusion criteria. Subsequent refinement using bibliographic management tools removed duplicates, yielding a final dataset of 411 articles for analysis (see Fig. 1).

Given that widely used scientometric tools such as Bibliometrix, VOSviewer, and CiteSpace primarily support English-language content—and considering the dominance of English publications in the Web of Science database—this study was confined to English-language literature to ensure methodological consistency and global comparability. It is recognized that this language restriction may introduce potential bias, which is further discussed in the limitations section.

Data export and preprocessing

The literature search was conducted on April 4, 2025, using the Web of Science Core Collection database, initially identifying 456 publications. After screening out records that did not meet the inclusion criteria—including non-article or non-review types (n=9), publications from non-SCI/SSCI journals (n=28), and non-English articles (n=6)—a total of 413 eligible publications were retained. These records were exported in plain-text format, preserving the "Full Record" and "Cited References" fields to ensure data completeness and analytical traceability.

The dataset was then imported into Zotero (7.0.15.0) for further manual validation and refinement, following the procedure below:

(1) Duplicate screening was conducted by comparing the "Title+First Author" fields, resulting in the removal of one duplicate entry.
(2) One entry erroneously labeled as "Book Section" was removed.
(3) Missing journal details were completed for two publications.
(4) Two documents incorrectly classified as "Book Section" but verified as journal articles were corrected accordingly.
(5) For the 20 publications lacking DOI information, manual verification was conducted using CrossRef, Google Scholar, PubMed, and the Web of Science (WoS) platform. Through this process, DOIs for 12 of the documents were successfully retrieved and supplemented. The remaining 8 articles, although still without DOIs, were retained in the dataset due to their strong thematic relevance to the core topics of this study—such as protein intake, creatine supplementation, resistance training, and muscle hypertrophy—and their relatively high citation frequencies in WoS. Upon careful manual screening, all retained articles were confirmed to be published in peer-reviewed international journals, including Neuroendocrinology Letters (Q4, cited up to 32 times), Journal of Sports Science and Medicine (Q2, cited up to 26 times), The Journal of Nutrition Health & Aging (Q1, cited 31 times), and Journal of Strength and Conditioning Research (Q1, cited 37 times). Despite the absence of DOIs, these studies

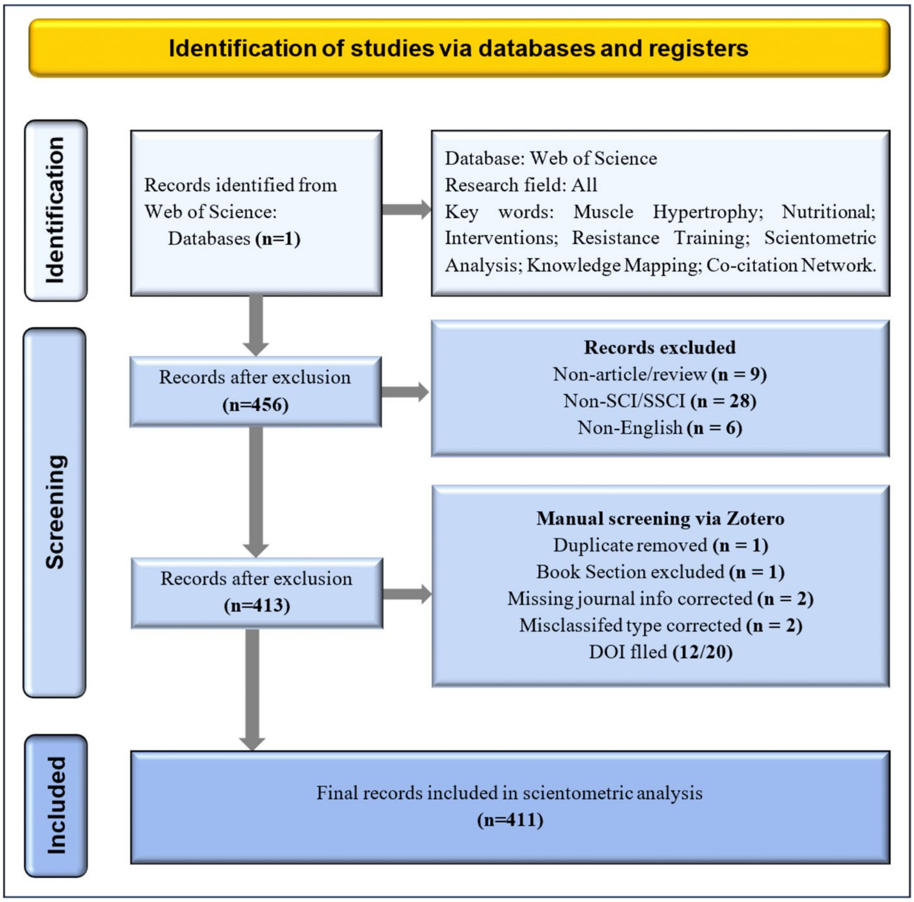


Fig. 1 PRISMA-style flow diagram of the literature screening and inclusion process for scientometric analysis. Note. A total of 456 articles were initially retrieved from Web of Science Core Collection. After applying eligibility criteria and manual validation (e.g., duplicate removal, metadata correction), 411 English-language articles were included in the final analysis

hold significant academic influence and relevance within the field. Their inclusion enhances the completeness of the dataset and supports the methodological rigor of the knowledge mapping process.

In total, 411 high-quality English-language articles were included in the final dataset for scientometric analysis. This rigorous data cleaning process ensured the accuracy and systematic integrity of the dataset, providing a reliable foundation for subsequent visualizations and structural analyses using tools such as Bibliometrix (R 4.4.3), VOSviewer (1.6.20), and CiteSpace (6.2.6).

It is important to note that the starting year of 1992 was deliberately chosen because it marks the earliest intersection of the three core topics—"nutritional intervention," "muscle hypertrophy," and "resistance training"—in the Web of Science database, signifying the initial emergence of systematic research in this domain. Among the final set of 411 included articles, only 12 were indexed as published in 2025, all of which were peer-reviewed and formally published papers. No preprints or unpublished manuscripts were included. The sole article labeled as "Early Access" had a publication year of 2024 (PD = 2024 SEP 24; PY = 2024), and thus does not compromise the integrity of the time boundary. Accordingly, the study's time span of 1992–2025 was strictly determined based on the retrieval window of the database as of April 4, 2025. This approach adheres to established norms for defining time boundaries in scientometric analyses, ensuring both data timeliness and academic validity.

Analytical tools and visualization methods

The formal analysis phase employed the following scientometric tools for multidimensional evaluation: Bibliometrix/Biblioshiny within the R language environment was used to analyze scientific output trends, keyword frequencies, author impact, and thematic evolution; VOSviewer was applied to construct keyword co-occurrence networks, author collaboration maps, and institutional collaboration networks; and

CiteSpace was used to detect emergent terms, trace thematic evolution trajectories, and visualize knowledge clusters. The integrated application of these tools enabled a comprehensive exploration of research hotspots, structural relationships, and future development directions within the intersecting domain of nutritional interventions, muscle hypertrophy, and resistance training.

To enhance the reproducibility and transparency of the analysis, clearly defined parameters were applied during the use of each analytical tool. In VOSviewer (v1.6.20), the minimum occurrence threshold for keyword co-occurrence analysis was set to 5. For country and institutional collaboration networks, the minimum publication thresholds were set to 1 and 3, respectively. Author-level visualization included the top 50 most productive authors, with full counting and default clustering algorithms applied throughout. In CiteSpace (v6.2.R6), co-citation clustering employed the g-index ($k=25$) as the node selection criterion, with a time slicing of one year and clustering based on the log-likelihood ratio (LLR) method. Citation burst and keyword burst detection were conducted using the Kleinberg algorithm with the following parameters: $\gamma=1.0$ (0.79 for keyword analysis), $\alpha_1/\alpha_0=2.0$, $\alpha_i/\alpha_{i-1}=2.0$, number of states $=2$, and a minimum burst duration of 2 years. Bibliometrix (R 4.4.3) and its web-based interface Biblioshiny were used for productivity analysis, keyword frequency statistics, author impact evaluation, and thematic evolution analysis, and also facilitated data preprocessing and relational matrix construction. These parameter settings ensured the clarity of the knowledge structures, the reproducibility of the analytical procedures, and the robustness of the study's findings.

Results

Main information

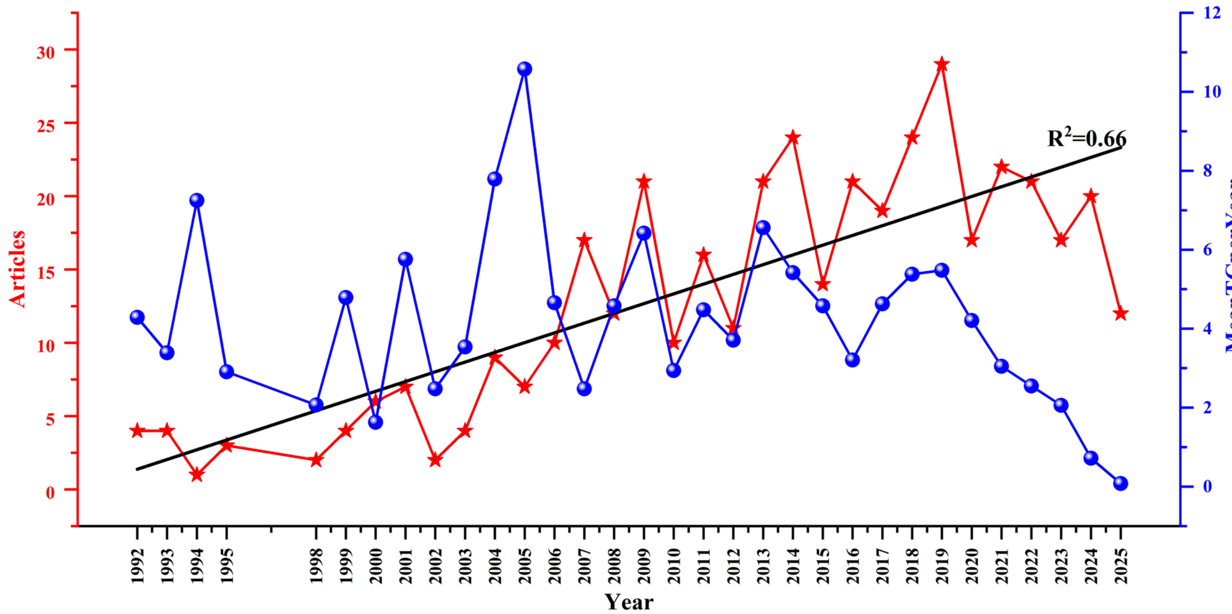
To systematically elucidate the fundamental structural features of research on nutritional interventions for muscle hypertrophy within the context of resistance training, this study conducted a comprehensive quantitative analysis and synthesis of 411 English-language publications. As illustrated in Fig. 2, the literature spans the period from 1992 to 2025, with an average annual growth rate of 3.39%. These publications are distributed across 138 academic sources and authored by 1728 researchers, including 17 single-author contributions. The average number of co-authors per article is 5.57, and the international collaboration rate stands at 29.68%, reflecting a relatively high level of team-based cooperation and global scholarly engagement. Collectively, these articles cite 14,535 references, with an average of 55.69 citations per publication. The average publication year is approximately 10.9 years prior to the present, indicating sustained academic influence and thematic continuity within the field. Additionally, a total of 800 author keywords were extracted, providing a robust semantic foundation for subsequent analyses of keyword co-occurrence patterns and thematic evolution.

Analysis of annual publication trends and academic impact

To comprehensively characterize the foundational research ecology of the "nutritional intervention–resistance training–muscle hypertrophy" domain, this study first conducts a systematic analysis of scientific output and collaboration patterns across four dimensions: countries, institutions, authors, and journals. This approach aims to elucidate the global distribution of academic resources and to identify the key contributors shaping the knowledge structure of this field.

To assess the long-term evolutionary trends within this research domain, Fig. 3 presents the annual number of

Fig. 2 Descriptive overview of publication metrics (1992–2025). Note. Key indicators include publication volume, author collaboration, international co-authorship, citation impact, and keyword frequency. See Sect. "Main information" for detailed explanations



Year	1992	1993	1994	1995	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Articles	4	4	1	3	2	4	6	7	2	4	9	7	10	17	12	21
MTCP	4.29	3.39	7.25	2.91	2.07	4.79	1.63	5.76	2.48	3.54	7.79	10.5	4.66	2.48	4.58	6.42

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Articles	10	16	11	21	24	14	21	19	24	29	17	22	21	17	20	12
MTCP	2.94	4.48	3.71	6.56	5.42	4.58	3.21	4.63	5.38	5.48	4.21	3.05	2.55	2.06	0.72	0.08

Fig. 3 Annual publication trend and citation impact of research on nutritional interventions in muscle hypertrophy (1992–2025). Note. The red line (left Y-axis) represents the annual number of publications (Articles), and the blue line (right Y-axis) indicates the Mean Total Citations per Year (MTCP). The black line shows the linear trend in publication output ($R^2 = 0.66$). The data illustrate a steady increase in publication activity over the past three decades, alongside a recent decline in citation impact for newly published articles

published articles and the Mean Total Citations per Year (MTCP) from 1992 to 2025. In the figure, the red line (left axis) indicates the yearly publication count, the blue line (right axis) shows the mean annual citation intensity, and the black fitted curve highlights the publication growth trend. As illustrated, the total number of publications has steadily increased over the observed period, exhibiting a strong linear trend ($R^2 = 0.66$), which underscores the growing research interest. Notably, a marked increase in annual publication output was observed from 2007 onward, reaching a peak in 2019 with 29 articles, reflecting a rapid rise in research activity over the past decade.

It is noteworthy that the trend of MTCP (Mean Total Citations per Year) does not fully align with the annual publication volume, reflecting a temporal lag between knowledge production and academic impact. For example, in the early phase, although only one article was published in 1994, it achieved an MTCP of 7.25; in 2001, seven publications yielded an MTCP of 5.76; and in 2005, with the same number of publications ($n = 7$), the MTCP reached as high as 10.58. These figures suggest that, despite limited output during this period, the published studies demonstrated substantial theoretical value. In the mid-development stage, publication output increased significantly, and the MTCP remained relatively stable—21 articles were published in both 2009 and 2013, with MTCPs of 6.42 and 6.56, respectively—indicating that the field had entered a mature phase characterized by both research productivity and citation accumulation.

In contrast, although 21 and 17 articles were published in 2022 and 2023, respectively, their MTCPs dropped to 2.55 and 2.06, indicating that these recent outputs are still in the early stages of citation accrual. The MTCP for 2025 was even lower at 0.08, primarily due to the data retrieval cutoff in April 2025, at which point the publications had not yet accumulated citations. This reflects a technical phenomenon of "citation lag" rather than a decline in research quality. Therefore, it is recommended that assessments of recent academic impact take into account the citation accumulation cycle and database update schedules to more accurately evaluate the long-term contribution potential of recent publications.

In summary, the field has demonstrated a consistent increase in publication output, reflecting growing academic interest. However, the immediate citation impact of recent publications remains relatively limited, indicating that future studies should prioritize not only quantitative expansion but also scientific originality and citation potential to enhance their overall scholarly value.

Multilevel analysis of scientific structure: country, institution, and author dimensions

National research output and scientific impact This section statistically analyzed research productivity and scholarly impact for the top 20 countries in the field from 1992 to 2025 (see Table 1), revealing global research patterns and knowledge leadership trends. The results indicate that research activities are predominantly concentrated in North America, Western Europe, and select Asia–Pacific countries, reflecting a research landscape characterized by regional dominance alongside multipolar coexistence.

From the perspective of research productivity (Table 1, left columns), the United States leads substantially with 398 publications, representing approximately one-third of total outputs, highlighting its extensive foundational research base and sustained leadership in this field. Brazil (119 articles) and Canada (94 articles) ranked second and third respectively, indicating high academic engagement in Latin America and North America. Other countries, such as the United Kingdom, Australia, Denmark, Japan, and China, also appear in the top ten, collectively constituting significant nodes within the global research framework.

Table 1 Top 20 countries by publication output and total citations (1992–2025)

Country	Freq (%)	Country	TC	Average article citations
USA	398 (29.97)	USA	8426	66.90
Brazil	119 (8.96)	Canada	3655	73.10
Canada	94 (7.08)	Netherlands	1503	115.60
UK	91 (6.85)	United Kingdom	1332	40.40
Australia	77 (5.80)	Australia	1219	55.40
Denmark	71 (5.35)	Denmark	1180	69.40
Japan	67 (5.05)	Japan	1012	46.00
China	53 (3.99)	Finland	622	77.80
South Korea	32 (2.41)	Brazil	612	19.70
Netherlands	30 (2.26)	Belgium	509	63.60
Finland	29 (2.18)	New Zealand	330	47.10
Iran	28 (2.11)	China	312	34.70
Spain	26 (1.96)	Germany	264	52.80
New Zealand	23 (1.73)	Switzerland	248	82.70
Belgium	22 (1.66)	Iran	221	31.60
Italy	22 (1.66)	Sweden	172	57.30
Germany	21 (1.58)	Norway	136	45.30
Poland	17 (1.28)	Singapore	110	55.00
Austria	13 (0.98)	France	95	47.50
Ireland	13 (0.98)	Korea	85	12.10

This table is constructed based on 411 publications retrieved from the Web of Science Core Collection (1992–2025), focusing on the theme of "nutritional intervention–resistance training–muscle hypertrophy." The left section ranks the top 20 countries by frequency of publication and corresponding percentage (Freq %), while the right section ranks the top 20 countries based on total citations (TC). Overall, 43 countries were represented with a cumulative publication frequency of 1328

In terms of scholarly influence, evaluated by total citations (TC) and average article citations (Table 1, right columns), the United States again ranks first with a total citation count of 8426, underscoring its international impact and dissemination capability. Countries such as Canada (3655 citations), the Netherlands (1503), Finland (622), Belgium (509), and Switzerland (248), despite fewer publications, have notably high average citation rates, each exceeding 60 citations per article. The Netherlands, in particular, ranks first in average citations per article (115.60), exemplifying a "small-scale, high-quality" research profile. These nations, despite limited publication outputs, have established substantial influence within the international academic community through their high average citation rates, solidifying their positions as prominent research entities.

Notably, although Brazil ranks second in productivity with 119 articles, its relatively low average citation count (19.70 citations per article) suggests a stage characterized by high output but comparatively limited scholarly impact. Consequently, future efforts should emphasize improving research quality and international visibility to strengthen academic influence.

Regarding Asian nations, China, South Korea, and Iran have experienced continuous growth in publication volume, with China ranking eighth (53 articles), reflecting an expanding research capacity in the Asia–Pacific region. However, these countries' average citation numbers (China: 34.70, South Korea: 12.10, Iran: 31.60) have not increased correspondingly, suggesting a mismatch between productivity and impact. This highlights the need for future initiatives to enhance originality and foster international collaborations to improve scholarly impact.

In summary, Table 1 illustrates that the United States maintains dual leadership in both research productivity and citation impact, establishing a global academic dominance in this area. Countries like the Netherlands, Finland, and Canada demonstrate high citation rates, emphasizing their research quality advantages. Furthermore, several smaller countries, despite limited output, achieve significant influence through high average citations, highlighting that both research quality and dissemination effectiveness are crucial for academic prominence. Overall, the research landscape in this domain presents a nonlinear distribution characterized by quantity-driven productivity alongside quality-driven breakthroughs. Emerging countries aiming for scholarly advancement should thus focus on expanding collaborative networks, enhancing research depth, and improving international dissemination capabilities.

High-producing institution analysis To further clarify the distribution and academic impact of core research institutions within the field of "nutritional intervention–resistance training–muscle hypertrophy," the top 20 institutions ranked by publication frequency from 1992 to 2025 were systematically identified and analyzed (Table 2). Given potential inconsistencies arising from institutional name variations and discrepancies across databases, manual standardization procedures were applied alongside VOSviewer's automatic identification function to ensure data accuracy and consistency (e.g., aggregating publication counts from multiple campuses under the University of Texas System).

Results indicated that McMaster University (Canada) led with 37 publications (3.55% of total) and 3526 total citations, highlighting its outstanding academic position in this research area. The team led by Professor Stuart M. Phillips at McMaster has systematically contributed theoretical frameworks regarding the synergistic mechanisms between protein supplementation, amino acid metabolism, and resistance training, proposing key insights into high-quality protein intake, nutrient timing, and optimization of muscle protein synthesis. These findings have been widely cited, significantly enhancing the institution's global academic influence.

The University of Texas System (USA) ranked second with 18 publications (1.73%) and 1871 total citations, exhibiting robust research productivity. Professor Kevin D. Tipton's group at this institution has concentrated on elucidating mechanisms through which protein intake before and after training influences muscle protein synthesis, notably pioneering comparisons between whey and casein protein metabolism. This research has driven protein supplementation strategies toward mechanistic precision and individualized application, substantially influencing the theoretical foundations of the field.

Maastricht University (Netherlands) ranked third with 14 publications (1.34%), achieving an impressive total of 2050 citations, corresponding to an average of over 146 citations per article. Similarly, institutions such as Tufts University (USA), with 9 publications and 1045 citations, and Copenhagen University Hospital Bispebjerg & Frederiksberg (Denmark), with 8 publications and 845 citations, demonstrated a highly focused and quality-driven research approach, further emphasizing significant qualitative differences among institutions.

Table 2 Top 20 research institutions ranked by publication frequency (1992–2025), including total citations and share of publications

Affiliation	Country	Freq (%)	TC
Mcmaster Univ	Canada	37 (3.55)	3526
University of Texas System	United States	18 (1.73)	1871
Maastricht Univ	Netherlands	14 (1.34)	2050
Univ Nottingham	United Kingdom	11 (1.06)	804
Univ Copenhagen	Denmark	10 (0.96)	952
Univ Kentucky	United States	10 (0.96)	740
Univ Regina	Canada	10 (0.96)	246
Univ Sao Paulo	Brazil	10 (0.96)	449
Aarhus Univ	Denmark	9 (0.86)	370
Tufts Univ	United States	9 (0.86)	1045
Univ Birmingham	United Kingdom	9 (0.86)	195
Univ of Arkansas System	United States	9 (0.86)	358
Auburn Univ	United States	8 (0.77)	187
Copenhagen Univ Hosp Bispebjerg & Frederiksberg	Denmark	8 (0.77)	845
Texas A&M Univ	United States	8 (0.77)	138
Univ Jyvaskyla	Finland	8 (0.77)	558
Univ Tampa	United States	8 (0.77)	338
Australian Catholic Univ	Australia	6 (0.58)	168
deakin Univ	Australia	6 (0.58)	198
Penn State Univ	United States	6 (0.58)	769

This table is constructed based on 411 publications from the Web of Science Core Collection (1992–2025), focusing on the topic of "nutritional intervention–resistance training–muscle hypertrophy." A total of 606 institutions with an aggregate publication frequency of 1041 were identified via VOSviewer. The table lists the top 20 institutions by publication frequency (Freq), along with their country affiliations, percentage of total publication frequency (%), and corresponding total citation counts (TC). As individual articles may be affiliated with multiple institutions, publication frequency (Freq), rather than the number of articles, was employed as the statistical metric

Regarding geographical distribution, Table 2 highlights the dominance of the United States, with 9 institutions appearing in the top 20, clearly reflecting national-level research system advantages. European universities such as the University of Copenhagen, Aarhus University (Denmark), the University of Nottingham, and the University of Birmingham (UK) maintained consistently high research activity, thereby sustaining momentum in Europe. Institutions from Australia, Brazil, and Finland also featured in the rankings, indicating increasing multipolar international research participation in this field.

Notably, although McMaster University had the highest publication output, its overall share was only 3.55%, and most other institutions represented less than 1% each, reflecting a broader institutional ecosystem characterized by collaborative participation and dispersed research capacity. This implies that despite a few core institutions guiding research trends, knowledge production remains relatively balanced and broadly collaborative across multiple institutions.

In conclusion, data from Table 2 demonstrate that institutions like McMaster University and the University of Texas System play pivotal roles in academic leadership within the "nutritional intervention–resistance training–muscle hypertrophy" research area. Meanwhile, institutions from different regions achieving high citation rates underscore the importance of quality-oriented research in enhancing international academic influence. Collectively, the institutional research landscape reveals a pattern of "core focus coupled with widespread participation," providing a robust foundation for future collaborative networks and knowledge dissemination.

High-producing authors and impact analysis Building on the institutional-level analysis, this section identifies the most prolific authors in the field and evaluates their academic influence and research foci, thereby highlighting key individual nodes within the knowledge network. Table 3 lists the top 20 most productive authors from 1992 to 2025 within the domain of “nutritional interventions–resistance training–muscle hypertrophy,” along with relevant Scientometric indicators.

The results reveal that Stuart M. Phillips (Phillips SM) stands out as the leading contributor in this domain, with 30 publications (1.31% of total publication frequency), 3021 total citations, and an h-index of 26—all the highest among the listed authors. Phillips’ foundational work demonstrated that resistance training combined with nutritional supplementation—particularly protein sources rich in essential amino acids and carbohydrates—synergistically enhances skeletal muscle protein synthesis (MPS) and promotes muscle hypertrophy [28]. In a widely cited 2004 review, Phillips argued that although resistance training may slightly elevate protein requirements, the habitual dietary intake of most athletes is generally sufficient, provided energy availability and nutrient timing are adequately managed [29]. In subsequent studies, Phillips and Van Loon emphasized that total protein intake, distribution frequency, and protein quality significantly affect adaptive responses to training. They recommended a daily intake of 1.3–1.8 g/kg of high-quality protein to optimize MPS and preserve lean body mass [30]. Moreover, their research highlighted the critical role of nutrient timing, protein source quality, and daily intake distribution in maximizing training adaptations. Across a series of landmark studies published between 2003 and the present—with cumulative citations exceeding one thousand—Phillips’ work systematically established the synergistic effects of combining high-quality protein supplementation with resistance training. These include stimulating MPS [31], inhibiting muscle protein breakdown (MPB), and attenuating age-related muscle loss (sarcopenia) [32], with further emphasis on the strategic timing of protein intake [33] and the modulation of intake patterns throughout the day [30]. Collectively, Phillips’ scholarly output has profoundly shaped the integration of protein metabolism, supplementation strategies, and resistance training, solidifying his sustained leadership within this interdisciplinary research area.

Closely following Phillips in prominence are Kevin D. Tipton, Daniel R. Moore, and Luc J.C. van Loon, who have also established comprehensive research frameworks surrounding protein metabolism, amino acid timing, and the synergistic mechanisms of training. Notably, Tipton and colleagues were among the first to demonstrate that ingesting either casein or whey protein after resistance exercise significantly enhances net muscle protein synthesis. Although these proteins differ in digestion rate and plasma amino acid kinetics, both elicit comparable anabolic responses, underscoring the effectiveness of whole-protein ingestion as a practical nutritional strategy for muscle hypertrophy [34].

As shown in Table 3, several prolific authors exhibit both high h-indices and substantial citation counts, reflecting the academic visibility and enduring influence of their work. For instance, L.J.C. van Loon (h = 12, TC = 2040), L.B. Verdijk (h = 9, TC = 1267),

Table 3 Top 20 high-producing authors and their academic impact metrics (1992–2025)

Authors	Freq (%)	Author	h_index	TC	PY_start
Phillips SM	30 (1.31)	Phillips SM	26	3021	2003
Tipton KD	13 (0.57)	Tipton KD	12	839	2001
Moore DR	12 (0.52)	Van Loon LJC	12	2040	2009
Van Loon LJC	12 (0.52)	Moore DR	11	1100	2005
Candow DG	10 (0.44)	Roberts MD	9	257	2013
Roberts MD	10 (0.44)	Verdijk LB	9	1267	2009
Smith K	10 (0.44)	Smith K	8	761	1992
Schoenfeld BJ	9 (0.39)	Wilson JM	8	487	2008
Verdijk LB	9 (0.39)	Breen L	7	191	2010
Atherton PJ	8 (0.35)	Campbell WW	7	766	1994
Wilson JM	8 (0.35)	Candow DG	6	246	2007
Breen L	7 (0.31)	Schoenfeld BJ	6	227	2013
Campbell WW	7 (0.31)	Atherton PJ	6	228	2011
Hulmi JJ	7 (0.31)	Hulmi JJ	6	541	2008
Joy JM	7 (0.31)	Joy JM	6	284	2013
Lowery RP	6 (0.26)	Lowery RP	6	280	2013
Mobley CB	6 (0.26)	Mobley CB	6	160	2014
Rasmussen BB	6 (0.26)	Rasmussen BB	6	722	2003
Van Kranenburg J	6 (0.26)	Van Kranenburg J	6	937	2013
Camera DM	5 (0.22)	De Souza EO	5	212	2013

This table is based on 411 sample publications retrieved from the Web of Science Core Collection (1992–2025), focusing on the research theme of "nutritional interventions–resistance training–muscle hypertrophy." It lists the top 20 most frequently publishing authors ranked by publication frequency (Freq). "Freq (%)" represents the proportion of each author’s publication frequency relative to the total frequency count of 2291 author contributions. h-index refers to each author’s Hirsch index within this specific research domain; TC denotes total citations; PY_start indicates the publication year of the author’s first article in this field. A total of 1728 unique authors contributed to the sample, with an accumulated publication frequency of 2291 and W.W. Campbell (h = 7, TC = 766) represent leading figures in the field. Additionally, senior researchers such as K. Smith, D.R. Moore, and B.B. Rasmussen began publishing as early as the 1990s and early 2000s, highlighting their long-standing contributions to foundational research. In contrast, emerging scholars including M.D. Roberts, J.M. Joy, and E.O. de Souza, who began publishing after 2010, are steadily building scholarly influence, reflecting the rise of a new generation of contributors.

From a structural perspective, most top authors account for less than 1% of the total publication frequency, suggesting a "core leadership–broad participation" model. Specifically, this pattern illustrates a decentralized yet collaborative research network in which academic leadership is complemented by broad-based community engagement. Prolific authors in this field tend to focus on critical themes such as protein and amino acid intake, anabolic signaling pathways, training intensity, and nutrient timing. The presence of well-established leaders—such as Phillips SM, Tipton KD, and van Loon LJC—alongside emerging contributors reflects an evolving, intergenerational research ecosystem. This structure provides a strong foundation for the continued advancement of research at the intersection of nutritional interventions and muscle hypertrophy.

In summary, the group of prolific authors in this research domain not only demonstrates substantial academic accumulation and widespread research influence but also reflects patterns of generational succession and geographical clustering in scholarly focus. To enhance the structural clarity of this section, the main findings are summarized as follows:

- *Prominent core leadership* Phillips SM, Tipton KD, and Van Loon LJC constitute the core author cluster in the integrated study of protein nutrition and resistance training. These authors have consistently produced high-quality research and exert significant academic influence.
- *Relatively concentrated research focus* Most prolific authors concentrate on key topics such as protein and amino acid intake, nutrient timing in relation to training, and mechanisms of muscle protein synthesis, forming stable collaborative networks within these focal areas.
- *Multi-centered author structure* The overall proportion of publications contributed by prolific authors remains relatively low, suggesting a "core minority–broad participation" pattern of knowledge production that supports thematic diversification and methodological innovation in the field.

It is worth noting that the prolific authors listed in Table 3 are predominantly affiliated with institutions in Europe and North America. Researchers from Asia have yet to form highly cited or high-output teams in this domain, highlighting the need for future efforts to strengthen regional research capacity and establish more inclusive international collaboration mechanisms.

National–institutional–author research structure integration analysis To further elucidate the organizational structure and collaborative patterns among research stakeholders within the domain of "nutritional interventions–resistance training–muscle hypertrophy," this study integrates the preceding analyses of national research output and impact (Sect. "National research output and scientific impact"; Table 1), institutional productivity (Sect. "High-producing institution analysis"; Table 2), and author-level influence (Sect. "High-producing authors and impact analysis"; Table 3). A three-field plot was generated using Bibliometrix/Biblioshiny to visualize and synthesize the interrelationships among countries, institutions, and authors (Figs. 4, 5, 6).

At the national level, Fig. 4 (with countries as central nodes) illustrates that the United States leads in both publication volume and citation impact, forming a dense, high-output knowledge network connected to prominent institutions (e.g., University of Texas System) and prolific authors (e.g., Tipton KD, Roberts MD, Rasmussen BB). In contrast, countries such as Canada and Denmark, though contributing fewer publications, demonstrate a quality-driven research structure, characterized by highly cited scholars (e.g., Phillips SM, Hulmi JJ) and influential institutions (e.g., McMaster University, University of Copenhagen), thereby occupying pivotal positions within the global collaboration network.

At the institutional level, Fig. 5 presents a three-field plot centered on institutions, revealing strong linkage patterns, with McMaster University (Canada) and the University of Copenhagen (Denmark) emerging as prominent nodes. These institutions exhibit both robust intra-institutional collaboration with domestic researchers and extensive academic outreach across multiple countries, thereby forming transnational and inter-institutional collaborative ecosystems. Notably, McMaster University is closely associated with leading authors such as Phillips SM and Moore DR, who appear as central hubs in the visual network, highlighting a positive correlation between institutional leadership and sustained scholarly output.

At the author level, Fig. 6 (author-centered) illustrates that scholars such as Phillips SM, Van Loon LJC, Moore DR, and Tipton KD occupy central positions within the collaborative network. Their affiliations span multiple

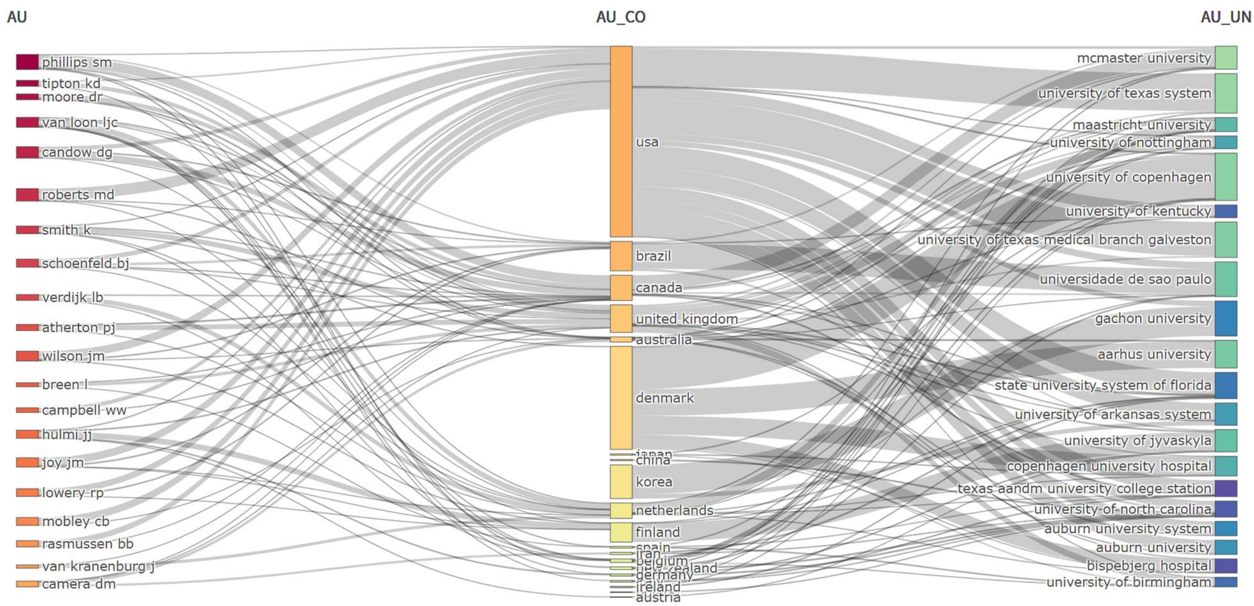


Fig. 4 Three-Field Plot: Authors–Countries–Institutions (with Country as the Central Node). Note: This figure presents a three-field collaboration map based on the literature data related to the topic "nutritional interventions–resistance training–muscle hypertrophy." It illustrates the cooperative patterns and linkage strengths among authors (left), countries (center), and institutions (right). Countries (AU_CO) serve as the central axis, reflecting international collaboration pathways and affiliations between authors (AU) and their institutions (AU_UN). The thickness of the lines indicates the frequency of collaboration, while node colors represent different entity types

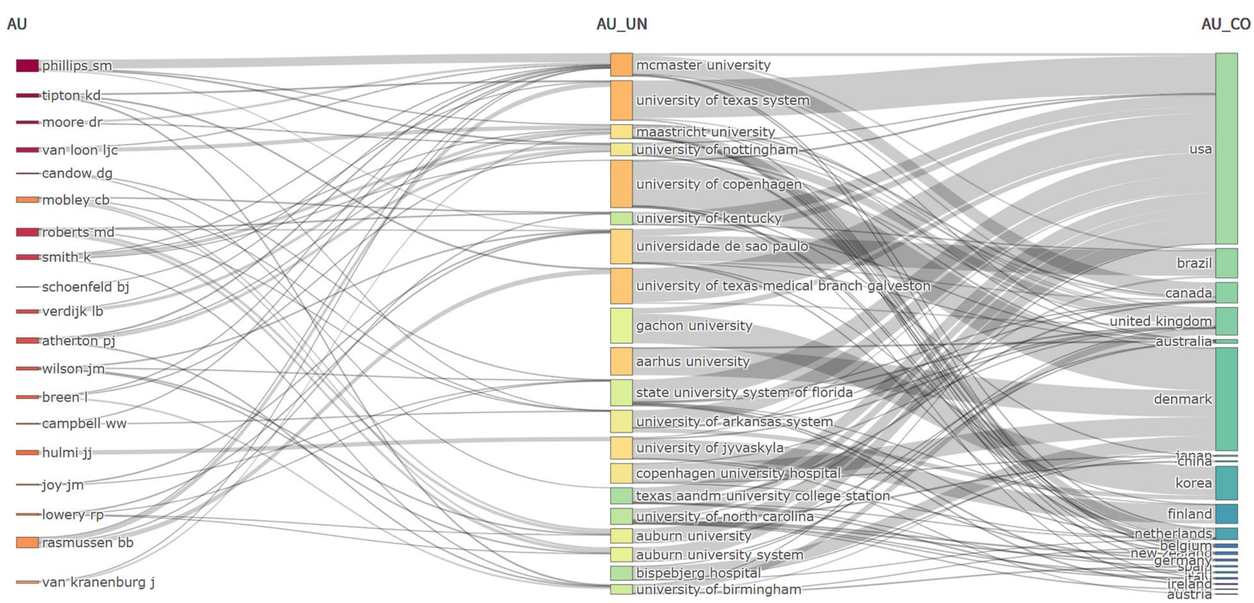


Fig. 5 Three-Field Plot: Authors–Institutions–Countries (Institution-Centered). Note: This figure maps a three-field collaboration structure with institutions (AU_UN) as the central axis, highlighting their pivotal role in cross-national research collaboration and author distribution. The left axis represents affiliated authors, while the right indicates associated countries. The dense external connections of institutions such as McMaster University and the University of Copenhagen illustrate their bridging role in the global academic landscape

institutions and countries, indicating that their academic influence extends beyond publication output to include extensive cross-institutional and international collaboration. Notably, emerging researchers such as Joy JM and Mobley CB have gradually integrated into these high-density collaboration networks, reflecting the growing global presence and cooperative capacity of the next generation of scholars.

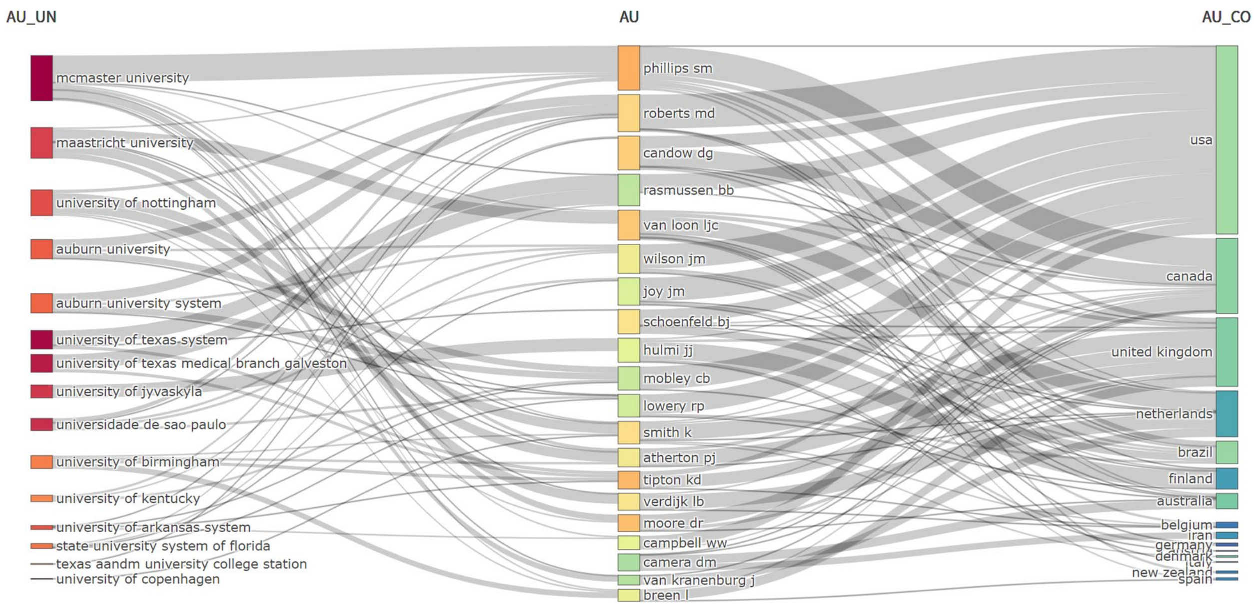


Fig. 6 Three-Field Plot: Institutions–Authors–Countries (Author-Centered). Note: This figure presents a collaboration network from the author perspective, with authors (AU) as central nodes linked to their affiliated institutions (AU_UN) on the left and countries (AU_CO) on the right. Results indicate that Phillips SM, Moore DR, and Van Loon LJC occupy key network positions, serving as conduits for multinational and inter-institutional knowledge exchange, thereby demonstrating their leadership and connectivity within the field

In summary, the Three-Field Plot shown in Figs. 4, 5 and 6 reveals a nested, interlinked model of "core countries–core institutions–core authors." The United States, supported by substantial research resources and institutional capacity, has established a highly centralized and efficient knowledge production system, positioning itself as the global leader in this domain. Meanwhile, countries such as Canada and Denmark have successfully integrated into the global academic network through high-quality research and strategic transnational collaborations. This structural coupling enhances both the efficiency of knowledge generation and the breadth of scholarly dissemination, providing critical insights into the global distribution of academic leadership and the mechanisms of knowledge diffusion.

Analysis of scientific collaboration networks among countries, institutions, and authors

Country-level collaboration network In the research domain of nutritional interventions, resistance training, and muscle hypertrophy, the national-level collaboration network exhibits a highly centralized and well-structured configuration. To enhance the visualization of inter-country collaboration patterns, a dual-panel representation was developed (see Fig. 7), integrating a cooperation network generated via VOSviewer with a geospatial distribution map constructed using Scimago Graphica. This composite visualization provides an intuitive depiction of the hierarchical positions and intensity of collaboration among countries within the global research landscape.

As illustrated in the figures, the United States occupies a central position in the collaboration network, serving as both the most prolific contributor and the primary hub for international cooperation. Countries such as Canada, the United Kingdom, Australia, Denmark, and the Netherlands maintain dense collaborative linkages with the United States, collectively forming a North America–Western Europe–centered scientific alliance. In contrast, although Asian countries such as China, Japan, and South Korea have demonstrated increasing publication output in recent years, their levels of network connectedness and centrality remain relatively low, reflecting a more peripheral status within the global collaboration structure.

Overall, the network reveals a core-periphery pattern, indicating that international research collaboration in this field continues to be dominated by a limited number of scientifically advanced nations. These core countries have established a compact, stable, and efficient global research system through frequent and closely integrated collaborations.

Institutional collaboration network As illustrated in Fig. 8, the institution-level collaboration network clearly reveals the structural characteristics and cooperative dynamics within the research domain of nutritional inter-

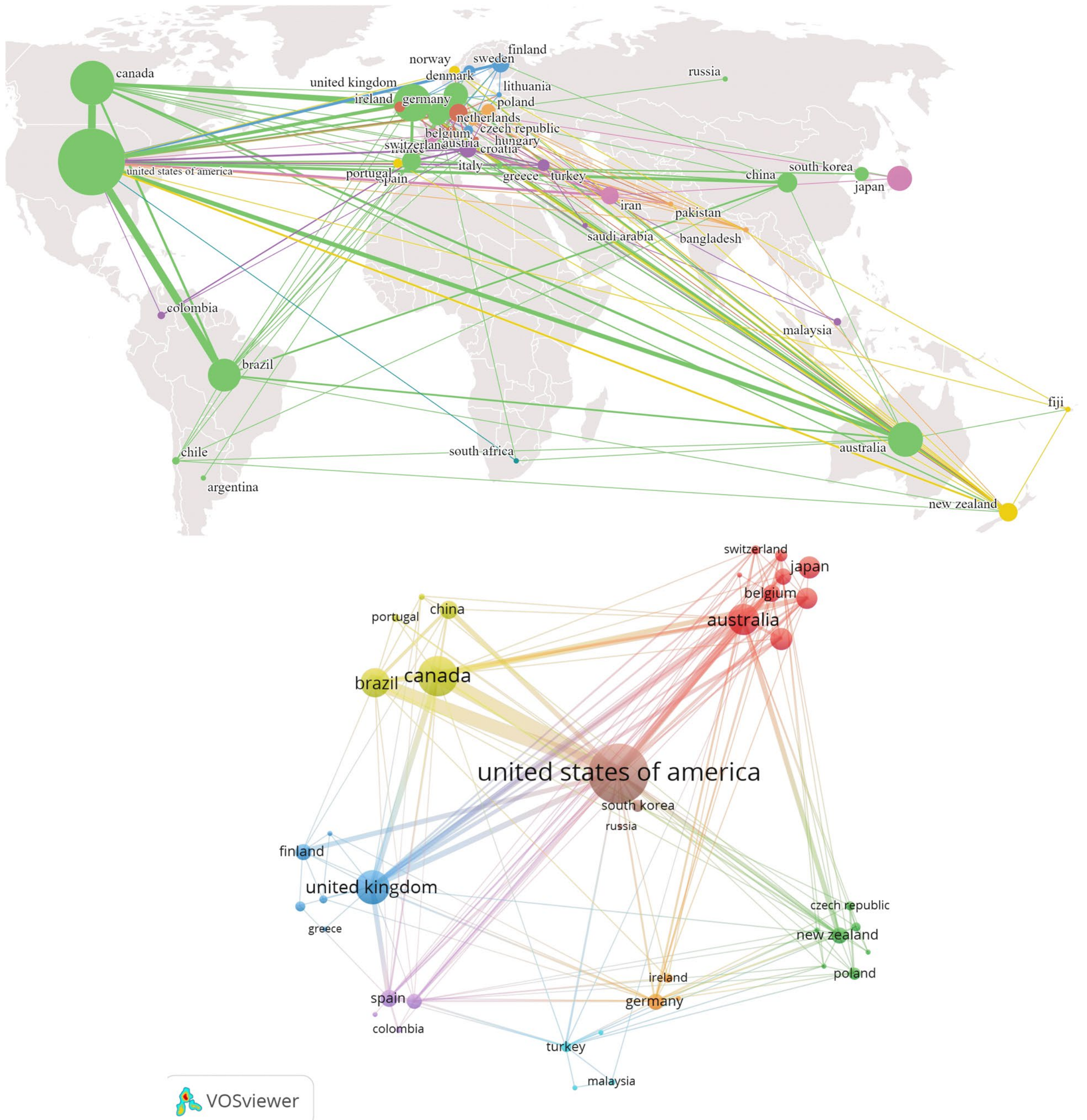


Fig. 7 Dual Visualization of International Collaboration Networks (1992–2025). Note: The top panel displays the global geographic distribution of research collaboration among countries, based on literature from the Web of Science Core Collection and visualized using VOSviewer and Scimago Graphica. Node size indicates the number of publications per country, and line thickness reflects the strength of international collaboration. The bottom panel presents the national-level collaboration network generated by VOSviewer, where node size corresponds to publication volume, edge thickness indicates collaboration frequency, and node color represents distinct collaboration clusters. Together, these visualizations illustrate the structural and spatial features of global collaboration in the research area of nutritional strategies and resistance training for muscle hypertrophy

ventions, resistance training, and muscle hypertrophy. The network demonstrates a multi-centered, cluster-oriented configuration, underscoring the cross-national and systematic nature of scholarly collaboration in this field.

Core institutions such as McMaster University, the University of Texas System, the University of Copenhagen, and the University of Arkansas System occupy central positions within the network. These institutions

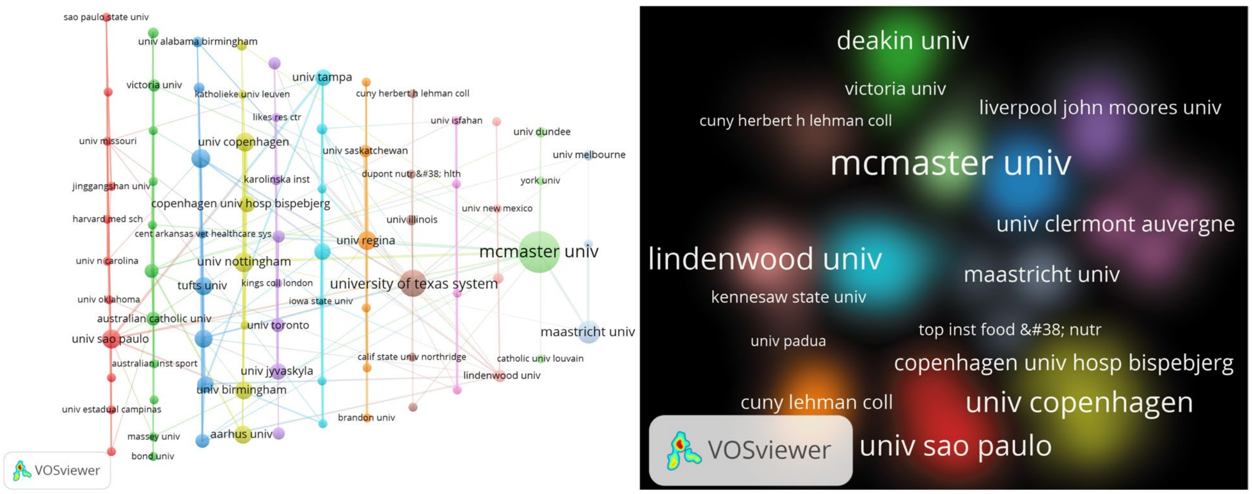


Fig. 8 Institutional Collaboration Network (1992–2025). Note: This figure is based on 411 publications retrieved from the Web of Science Core Collection, focusing on the topic of nutritional interventions in resistance training-induced muscle hypertrophy. The data were processed using VOSviewer, selecting 88 institutions with at least three publications. Records involving more than 25 collaborating institutions per article were excluded to enhance network clarity. In the visualization, node size indicates the number of publications per institution, edge thickness represents collaboration strength, and color reflects distinct collaboration clusters. Font size in the heatmap is proportional to collaboration strength

not only lead in publication output but also function as critical hubs that connect diverse research groups through international collaborations.

The visualization indicates that these high-output institutions typically leverage domestic research strengths to establish dense international co-authorship networks. For instance, McMaster University, which leads with 37 publications, also demonstrates a collaboration strength of 21—substantially above the network average—highlighting its leadership in the global research landscape. Similarly, institutions such as the University of Copenhagen, the University of Kentucky, and the University of São Paulo exhibit high collaboration strengths, reflecting their proactive engagement and influence in international research cooperation.

Notably, some institutions with relatively lower publication outputs—such as Lindenwood University, the University of Central Florida, and the University of Isfahan—have nonetheless achieved high network connectivity through close partnerships with leading institutions. This suggests that strategic collaboration not only enhances research quality and visibility but also enables lower-output institutions to amplify their academic impact.

Overall, the institutional collaboration network reflects a multi-layered cooperative system driven by two key dimensions: research productivity (publication volume) and collaborative engagement (collaboration strength). The presence of tightly interconnected clusters facilitates thematic integration and knowledge diffusion, contributing to the growing globalization and maturity of this research field.

Author collaboration network The author collaboration network presented in Fig. 9 provides a systematic visualization of the collaborative research structure within the domain of "nutritional interventions–resistance training–muscle hypertrophy." The overall network demonstrates a typical clustered distribution, indicating that academic cooperation in this field is organized around several stable author groups that have formed tightly interconnected research communities. Core authors such as Phillips SM, Roberts MD, and Van Loon LJC occupy key positions within the network. These scholars are not only highly prolific but also maintain extensive collaborative ties, serving as major drivers of knowledge production and dissemination in the field. These leading researchers have established high-frequency collaboration networks both within their home institutions and across international boundaries, thereby significantly enhancing the visibility and impact of their scientific contributions. In contrast, some authors with relatively modest publication volumes have nonetheless achieved notable network centrality through close collaborations with core researchers, underscoring the strategic role of partnerships in elevating scientific participation and academic visibility.

Overall, the network reflects a stratified structure and aggregation effect in author-level research collaboration, highlighting the dominant role of top-tier authors in

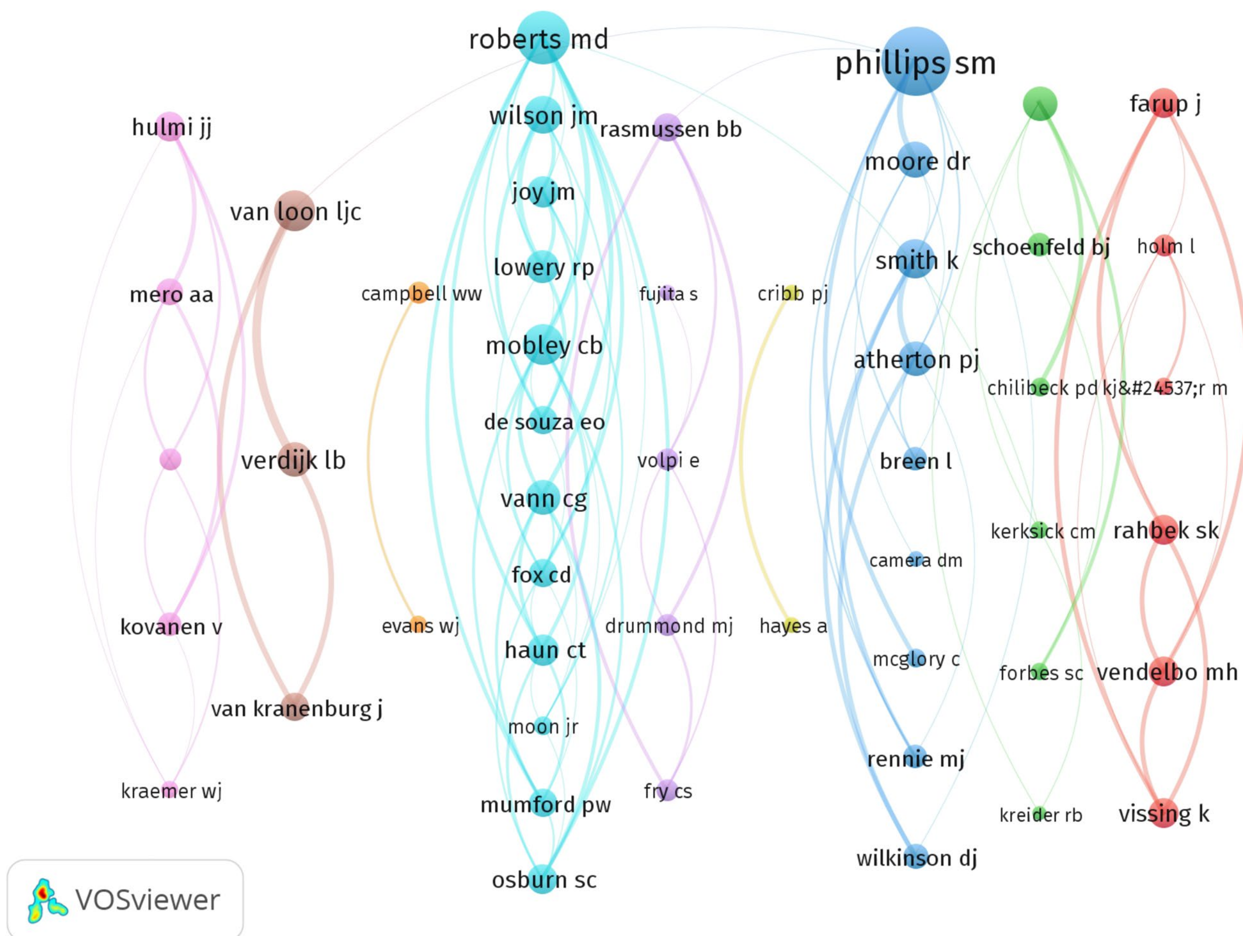


Fig. 9 Author Collaboration Network in the Field of Nutritional Interventions, Resistance Training, and Muscle Hypertrophy (1992–2025). Note: This figure is constructed based on 411 publications retrieved from the Web of Science Core Collection on the topic of nutritional interventions, resistance training, and muscle hypertrophy. Using the author collaboration matrix generated by Bibliometrix, the author-level collaboration network was visualized with VOSviewer. Each node represents an individual author, with node size indicating the number of publications and edge thickness reflecting the strength of collaboration. Different colors represent distinct collaborative clusters. To ensure visual clarity and analytical precision, the visualization includes the top 50 most prolific authors based on publication frequency. The original network was further refined and enhanced for improved structural clarity and readability of author collaborations

advancing knowledge innovation and shaping the disciplinary evolution within this domain.

In summary, based on the integrated analysis of research structures and collaboration networks at the levels of countries, institutions, and authors, it is evident that the field of "nutritional interventions–resistance training–muscle hypertrophy" has developed a multi-tiered and structured international scientific collaboration system, with the United States at its core. At the national level, the U.S. has established a globally dominant position through its substantial research output and extensive international collaboration network. Countries such as Canada, the United Kingdom, and Denmark have embedded themselves within the core of this network via high-quality publications and active transnational partnerships, whereas emerging powers such as China, Japan, and South Korea remain in a peripheral expansion phase, reflecting a core–periphery dynamic.

At the institutional level, high-output institutions such as McMaster University, the University of Texas System, and the University of Copenhagen are not only prolific in terms of publication but also function as central hubs connecting authors and countries, thereby forming transnational collaboration networks anchored by leading institutions. At the author level, influential scholars such as Phillips SM and Van Loon LJC have constructed dense collaborative clusters through long-term, stable, multi-institutional, and international partnerships, thereby accelerating knowledge dissemination and disciplinary development.

Overall, this field demonstrates a clearly nested collaborative structure encompassing countries, institutions, and authors. Research output, collaboration intensity, and academic influence are highly interconnected, and the collaborative network is characterized by strong centralization, the dominance of a few key actors, and multipolar interaction. This structure provides a robust foundation for future knowledge integration and interdisciplinary convergence.

Analysis of core journals and citation structure

Leading journals: research output and scholarly impact To identify the primary platforms for scholarly dissemination within this research domain, a quantitative analysis was conducted on journals that published articles related to nutritional interventions, resistance training, and muscle hypertrophy from 1992 to 2025 (see Table 4). Indicators such as the number of publications (Articles), Hirsch index (h-index), total citations (TC), and the year of first publication (PY_start) were integrated to assess research productivity and scholarly influence.

As shown in Table 4, Nutrients ranked first with 21 publications (5.11%), reflecting its rapid rise as a leading open-access journal in sports nutrition. Notably, despite initiating relevant publications only in 2016, Nutrients has become the most prolific outlet in this domain, underscoring the growing influence of open-access platforms in enhancing research visibility.

Other highly active journals include the Journal of the International Society of Sports Nutrition, Medicine and Science in Sports and Exercise, and Sports Medicine (each with 18 publications, 4.38%). Among them, Sports Medicine stands out with the highest total citations (TC = 2229) and an h-index of 14, establishing it as one of the most impactful journals in the field. It frequently publishes systematic reviews and empirical studies, serving as a pivotal platform for policy formulation and clinical application.

The Journal of Applied Physiology also demonstrates significant academic influence, with 16 publications (3.89%), 1856 total citations, and an h-index of 12, highlighting its relevance to research on muscle metabolism, training adaptation, and nutritional regulation. Similarly, although the American Journal of Clinical Nutrition published only 7 articles (1.70%), it garnered 1061 citations, reaffirming its authoritative position in core nutritional science.

Table 4 Core journals in the field of nutritional interventions and resistance training-induced muscle hypertrophy: research output and impact metrics (1992–2025)

Sources	Articles (%)	h_index	TC	PY_start
NUTRIENTS	21 (5.11)	10	594	2016
JOURNAL OF THE INTERNATIONAL SOCIETY OF SPORTS NUTRITION	18 (4.38)	14	546	2005
MEDICINE AND SCIENCE IN SPORTS AND EXERCISE	18 (4.38)	17	1617	1992
SPORTS MEDICINE	18 (4.38)	14	2229	1999
JOURNAL OF APPLIED PHYSIOLOGY	16 (3.89)	12	1856	2005
FRONTIERS IN NUTRITION	13 (3.16)	8	261	2018
INTERNATIONAL JOURNAL OF SPORT NUTRITION AND EXERCISE METABOLISM	13 (3.16)	9	286	2000
NUTRITION	13 (3.16)	10	597	2004
APPLIED PHYSIOLOGY NUTRITION AND METABOLISM	12 (2.92)	10	575	2006
EUROPEAN JOURNAL OF APPLIED PHYSIOLOGY	11 (2.68)	9	523	2005
AMERICAN JOURNAL OF PHYSIOLOGY-ENDOCRINOLOGY AND METABOLISM	10 (2.43)	10	1285	1995
JOURNAL OF STRENGTH AND CONDITIONING RESEARCH	10 (2.43)	8	322	1998
NUTRITION & METABOLISM	9 (2.19)	9	652	2008
FRONTIERS IN PHYSIOLOGY	8 (1.95)	7	362	2015
JOURNAL OF NUTRITION	8 (1.95)	7	452	1992
AMERICAN JOURNAL OF CLINICAL NUTRITION	7 (1.70)	7	1061	1994
CURRENT OPINION IN CLINICAL NUTRITION AND METABOLIC CARE	7 (1.70)	7	826	2001
EXPERIMENTAL GERONTOLOGY	6 (1.46)	6	716	2013
JOURNAL OF THE AMERICAN COLLEGE OF NUTRITION	6 (1.46)	6	496	1995
STRENGTH AND CONDITIONING JOURNAL	6 (1.46)	3	60	2012

This table is based on a total of 411 articles published between 1992 and 2025, focusing on the research topic of nutritional interventions, resistance training, and muscle hypertrophy. It lists the top 20 core journals ranked by the number of publications. Key indicators include journal name (Sources), number and percentage of articles published (Articles [%]), Hirsch index (h_index), total citations (TC), and the publication year of the first relevant article (PY_start). These metrics were used to comprehensively assess each journal's research activity and academic impact within the field. In total, 411 articles were published across 138 different journals

Emerging journals such as Frontiers in Nutrition (13 articles, 3.16%) and Nutrition & Metabolism (9 articles, 2.19%) have exhibited strong growth in recent years, suggesting a shift among researchers toward greater emphasis on transparency, open-access dissemination, and global reach. These platforms also contribute to the accelerated translation of research into clinical practice and public health initiatives. Collectively, the top 20 journals account for approximately 55.72% of all publications (229 out of 411), indicating a relatively centralized publishing landscape within this thematic area. Such concentration allows researchers to strategically target high-impact outlets for knowledge dissemination.

In summary, Table 4 highlights an evolving publication landscape in which research on nutritional interventions for muscle hypertrophy via resistance training is transitioning from traditional authoritative journals to diversified, open-access platforms. The research paradigm is expanding from mechanistic foundations toward interdisciplinary integration across clinical application, exercise rehabilitation, and precision nutrition.

Based on the integrated analysis of quantitative indicators and trend assessments, the key findings can be summarized as follows:

- *Divergence between research productivity and citation impact* For instance, Nutrients ranked highest in publication volume, yet its total citations and h-index were lower than those of traditional journals, indicating that high output does not necessarily equate to high citation impact.
- *Dominance of authoritative journals* Traditional high-impact journals such as Sports Medicine and Journal of Applied Physiology maintain a clear advantage in both citation frequency and bibliometric influence, underscoring their continued leadership in the field.
- *Rapid rise of open-access platforms* Emerging journals such as Frontiers in Nutrition and Nutrients have exhibited noticeable growth in publication frequency and dissemination scope, reflecting an increasing trend toward greater research visibility and accessibility.
- *Increasing convergence of research paradigms* The journal distribution spans multiple disciplines, including exercise science, clinical nutrition, and physiology, suggesting a thematic shift from basic research toward translational practice and interdisciplinary integration.

Citation structure analysis To further elucidate the knowledge base and developmental trajectory of research in the field of "nutritional interventions—resistance training—muscle hypertrophy," this study employed CiteSpace to conduct a co-citation analysis of references cited in publications from 1992 to 2025. A co-citation network of core knowledge units (Fig. 10) and a visualization of citation burst intensity (Fig. 11) were generated. These were then systematically examined in conjunction with the top 20 references ranked by burst strength, as presented in Table 5.

The co-citation network (Fig. 10) reveals a typical core–periphery structure within the field's knowledge architecture. The overall network density is 0.0072, indicating a moderate level of interconnectivity among knowledge nodes without strong centralization. Highly cited references, including those by Moore DR (2009), Tipton KD (2003, 2004, 2007), Phillips SM (2004), and Tang JE (2009), form tightly interlinked clusters that constitute the foundational literature in this domain. Notably, the reference by Morton RW (2018) demonstrates both frequent co-citation and high betweenness centrality (0.16), signifying its pivotal role as a conceptual bridge and turning point within the citation network.

The citation burst analysis further traces the evolution of research hotspots over distinct time periods (Fig. 11). For example, the works of Tang JE (2009) and Cermak NM (2012) exhibit prominent citation bursts between 2010 and 2017, reflecting intensified academic attention on topics such as protein timing and the efficacy of nutritional interventions. Of particular importance is Morton RW (2018), whose study shows an exceptionally high burst strength of 18.42 extending through 2023, identifying it as a foundational citation in current research focal points. Table 5 provides detailed metadata on these burst references, including author, source journal, burst period, and centrality—demonstrating that high burst intensity and high centrality often co-occur, marking pivotal nodes of paradigm shifts within the field.

In summary, the citation structure analysis reveals that the knowledge base of the "nutritional interventions—resistance training—muscle hypertrophy" field is predominantly built upon high-impact studies focusing on protein metabolism regulation, timing of nutritional intake, and resistance training strategies. The developmental trajectory reflects a progression from early explorations of protein requirements toward more mechanistic and optimization-driven approaches in intervention design.

Research hotspots: trends in the integration of nutritional strategies and training modalities

To systematically identify the mainstream research pathways and thematic hotspots concerning nutritional

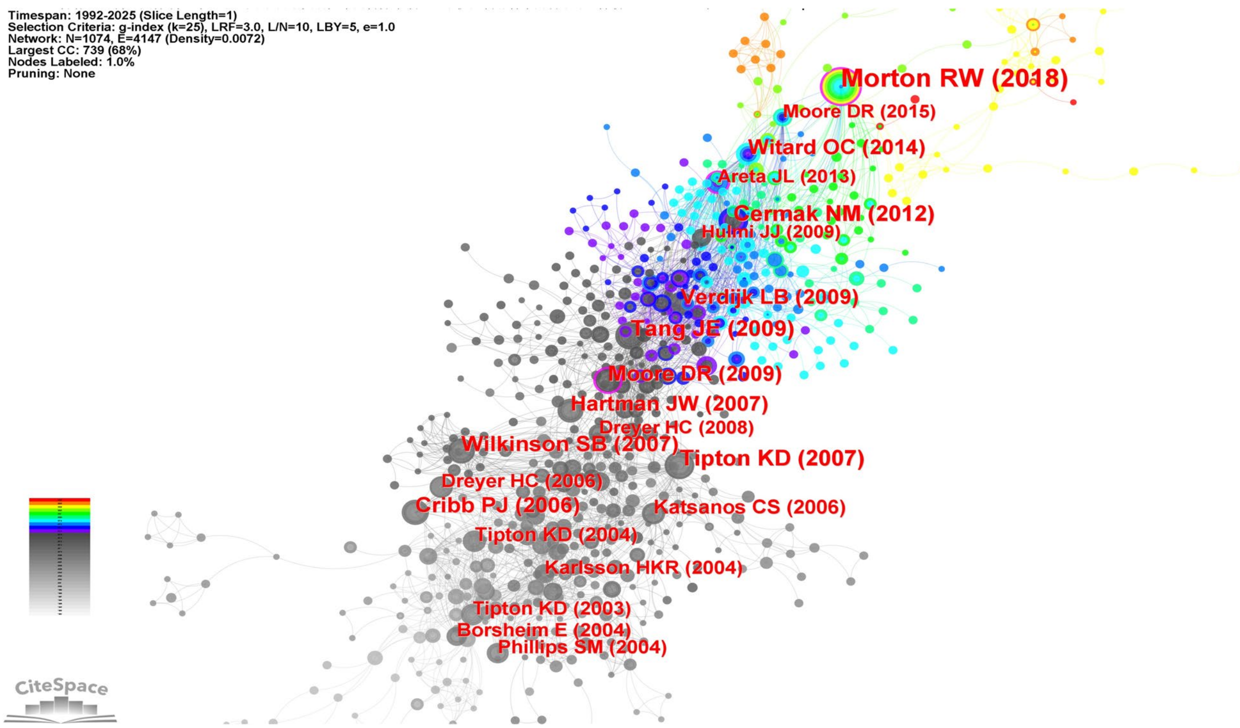
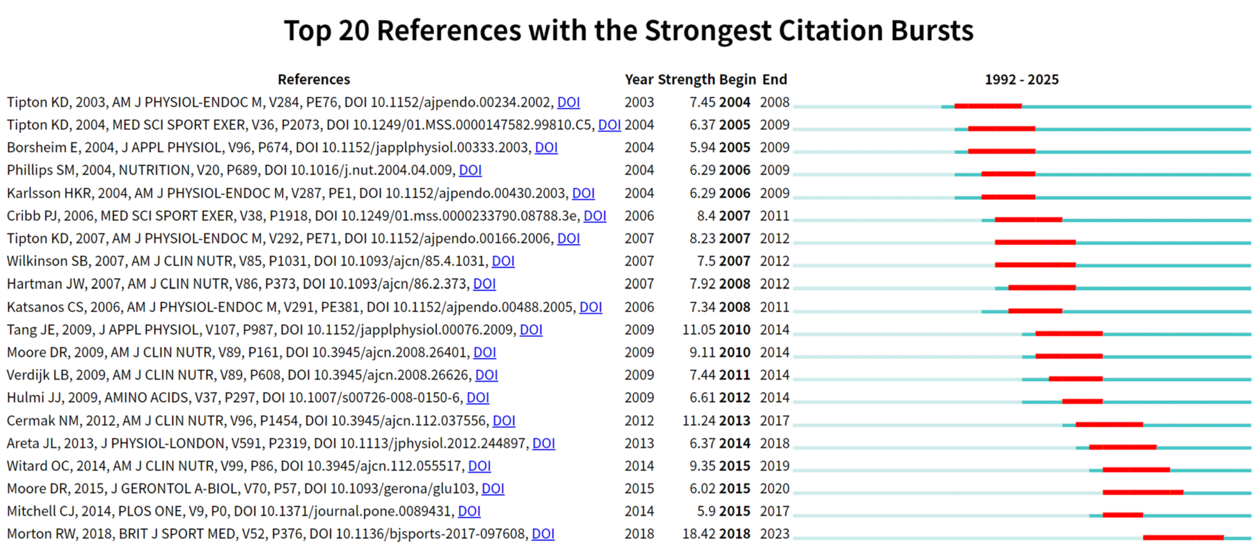


Fig. 10 Co-Citation Network of References in the Field of Nutritional Interventions—Resistance Training—Muscle Hypertrophy (1992–2025). Note: Each node in the figure represents a co-cited reference; node size reflects the frequency of co-citation, while colors indicate different citation clusters. Edges represent co-citation links, with denser and more frequent connections suggesting stronger thematic relevance between references. The network was constructed based on the references cited in 411 core publications from 1992 to 2025, resulting in a total of 1074 nodes and 4147 edges, with a network density of 0.0072. Key nodes with high co-citation frequency and centrality—such as Moore DR (2009), Tipton KD (2007), and Morton RW (2018)—are highlighted in red, indicating foundational literature in this field. These works emphasize core research themes such as muscle protein synthesis, timing of protein intake, and nutritional intervention strategies



Top 20 References with the Strongest Citation Bursts

References	Year	Strength	Begin	End	1992 - 2025
Tipton KD, 2003, AM J PHYSIOL-ENDOC M, V284, PE76, DOI 10.1152/ajpendo.00234.2002, DOI	2003	7.45	**2004**	2008	
Tipton KD, 2004, MED SCI SPORT EXER, V36, P2073, DOI 10.1249/01.MSS.0000147582.99810.C5, DOI	2004	6.37	**2005**	2009	
Borsheim E, 2004, J APPL PHYSIOL, V96, P674, DOI 10.1152/japplphysiol.00333.2003, DOI	2004	5.94	**2005**	2009	
Phillips SM, 2004, NUTRITION, V20, P689, DOI 10.1016/j.nut.2004.04.009, DOI	2004	6.29	**2006**	2009	
Karlsson HKR, 2004, AM J PHYSIOL-ENDOC M, V287, PE1, DOI 10.1152/ajpendo.00430.2003, DOI	2004	6.29	**2006**	2009	
Cribb PJ, 2006, MED SCI SPORT EXER, V38, P1918, DOI 10.1249/01.mss.0000233790.08788.3e, DOI	2006	8.4	**2007**	2011	
Tipton KD, 2007, AM J PHYSIOL-ENDOC M, V292, PE71, DOI 10.1152/ajpendo.00166.2006, DOI	2007	8.23	**2007**	2012	
Wilkinson SB, 2007, AM J CLIN NUTR, V85, P1031, DOI 10.1093/ajcn/85.4.1031, DOI	2007	7.5	**2007**	2012	
Hartman JW, 2007, AM J CLIN NUTR, V86, P373, DOI 10.1093/ajcn/86.2.373, DOI	2007	7.92	**2008**	2012	
Katsanos CS, 2006, AM J PHYSIOL-ENDOC M, V291, PE381, DOI 10.1152/ajpendo.00488.2005, DOI	2006	7.34	**2008**	2011	
Tang JE, 2009, J APPL PHYSIOL, V107, P987, DOI 10.1152/japplphysiol.00076.2009, DOI	2009	11.05	**2010**	2014	
Moore DR, 2009, AM J CLIN NUTR, V89, P161, DOI 10.3945/ajcn.2008.26401, DOI	2009	9.11	**2010**	2014	
Verdijk LB, 2009, AM J CLIN NUTR, V89, P608, DOI 10.3945/ajcn.2008.26626, DOI	2009	7.44	**2011**	2014	
Hulmi JJ, 2009, AMINO ACIDS, V37, P297, DOI 10.1007/s00726-008-0150-6, DOI	2009	6.61	**2012**	2014	
Cermak NM, 2012, AM J CLIN NUTR, V96, P1454, DOI 10.3945/ajcn.112.037556, DOI	2012	11.24	**2013**	2017	
Areta JL, 2013, J PHYSIOL-LONDON, V591, P2319, DOI 10.1113/jphysiol.2012.244897, DOI	2013	6.37	**2014**	2018	
Witard OC, 2014, AM J CLIN NUTR, V99, P86, DOI 10.3945/ajcn.112.055517, DOI	2014	9.35	**2015**	2019	
Moore DR, 2015, J GERONTOL A-BIOL, V70, P57, DOI 10.1093/gerona/glu103, DOI	2015	6.02	**2015**	2020	
Mitchell CJ, 2014, PLOS ONE, V9, P0, DOI 10.1371/journal.pone.0089431, DOI	2014	5.9	**2015**	2017	
Morton RW, 2018, BRIT J SPORT MED, V52, P376, DOI 10.1136/bjsports-2017-097608, DOI	2018	18.42	**2018**	2023	

Fig. 11 Top 20 References with the Strongest Citation Bursts. Note: This figure displays the top 20 references identified as having the strongest citation bursts between 1992 and 2025. Burst strength reflects the intensity with which a publication was cited within a specific period, indicating a concentrated surge of academic attention. Red line segments represent the time spans during which the bursts occurred. References such as Morton RW (2018), Tang JE (2009), and Cermak NM (2012) reveal the temporal evolution of critical theoretical breakthroughs and research hotspots within this domain

Table 5 Top 20 references with the strongest citation bursts in the field of nutritional interventions—resistance training—muscle hypertrophy (1992–2025)

Author (year)	Burst strength	Burst period	Centrality	Source	DOI
Tipton KD (2003)	7.45	2004–2008	0.05	AM J PHYSIOL-ENDOC M	https://doi.org/10.1152/ajpendo.00234.2002
Tipton KD (2004)	6.37	2005–2009	0.02	MED SCI SPORT EXER	https://doi.org/10.1249/01.MSS.0000147582.99810.C5
Borsheim E (2004)	5.94	2005–2009	0.05	J APPL PHYSIOL	https://doi.org/10.1152/japplphysiol.00333.2003
Phillips SM (2004)	6.29	2006–2009	0.01	NUTRITION	https://doi.org/10.1016/j.nut.2004.04.009
Karlsson HKR (2004)	6.29	2006–2009	0.01	AM J PHYSIOL-ENDOC M	https://doi.org/10.1152/ajpendo.00430.2003
Cribb PJ (2006)	8.4	2007–2011	0.02	MED SCI SPORT EXER	https://doi.org/10.1249/01.mss.0000233790.08788.3e
Tipton KD (2007)	8.23	2007–2012	0.08	AM J PHYSIOL-ENDOC M	https://doi.org/10.1152/ajpendo.00166.2006
Wilkinson SB (2007)	7.5	2007–2012	0.05	AM J CLIN NUTR	https://doi.org/10.1093/ajcn/85.4.1031
Hartman JW (2007)	7.92	2008–2012	0.01	AM J CLIN NUTR	https://doi.org/10.1093/ajcn/86.2.373
Katsanos CS (2006)	7.34	2008–2011	0.06	AM J PHYSIOL-ENDOC M	https://doi.org/10.1152/ajpendo.00488.2005
Tang JE (2009)	11.05	2010–2014	0.09	J APPL PHYSIOL	https://doi.org/10.1152/japplphysiol.00076.2009
Moore DR (2009)	9.11	2010–2014	0.12	AM J CLIN NUTR	https://doi.org/10.3945/ajcn.2008.26401
Verdijk LB (2009)	7.44	2011–2014	0.01	AM J CLIN NUTR	https://doi.org/10.3945/ajcn.2008.26626
Hulmi JJ (2009)	6.61	2012–2014	0.02	AMINO ACIDS	https://doi.org/10.1007/s00726-008-0150-6
Cermak NM (2012)	11.24	2013–2017	0.05	AM J CLIN NUTR	https://doi.org/10.3945/ajcn.112.037556
Areta JL (2013)	6.37	2014–2018	0.12	J PHYSIOL-LONDON	https://doi.org/10.1113/jphysiol.2012.244897
Witard OC (2014)	9.35	2015–2019	0.05	AM J CLIN NUTR	https://doi.org/10.3945/ajcn.112.055517
Moore DR (2015)	6.02	2015–2020	0.04	J GERONTOL A-BIOL	https://doi.org/10.1093/gerona/glu103
Mitchell CJ (2014)	5.9	2015–2017	0	PLOS ONE	https://doi.org/10.1371/journal.pone.0089431
Morton RW (2018)	18.42	2018–2023	0.16	BRIT J SPORT MED	https://doi.org/10.1136/bjsports-2017-097608

This table is based on CiteSpace citation burst analysis of 413 core publications from 1992 to 2025. It lists the top 20 references with the highest burst strength, along with their burst period and betweenness centrality. Burst strength denotes the intensity of abrupt citation increases during specific time intervals; burst period indicates when the citation burst occurred; centrality measures the reference's intermediary role within the co-citation network, reflecting its significance in the academic information flow. These results help identify key knowledge peaks and milestone publications in the developmental trajectory of the field

interventions and resistance training in muscle hypertrophy studies, this section conducts a multidimensional analysis across four key dimensions:

(1) the research prominence of nutritional strategies;
(2) the adoption trends of various training modalities;
(3) preferences in the combination of nutrition and training approaches;
(4) structural co-occurrence patterns among keywords.

By integrating keyword frequency statistics (Table 6), a "Nutrition × Training" co-occurrence matrix (Table 7), and the author keyword co-occurrence network (Fig. 12), this analysis offers a comprehensive overview of the domain's research characteristics, particularly in terms of intervention directions, training attributes, and variable interlinkages.

Overview of author keyword frequencies: muscle hypertrophy and resistance training as core research themes

According to the frequency ranking of author keywords (see Table 6), the research focus is predominantly centered on variables such as "muscle hypertrophy" (74 occurrences), "resistance training" (46 occurrences), "exercise" (43 occurrences), "resistance exercise" (40 occurrences), and "strength training" (31 occurrences). These findings suggest that the current literature primarily adopts a research model grounded in resistance training–induced muscle growth, thereby establishing a core framework based on the interplay between training stimuli and structural adaptation.

With regard to intervention modalities, high-frequency keywords such as "nutrition" (31 occurrences), "protein" (27 occurrences), "amino acids" (21 occurrences), "creatine" (18 occurrences), and "whey protein" (18) underscore the central role of protein intake and supplementation strategies in facilitating muscle development. Furthermore, the frequent appearance of terms such as "sarcopenia" (42 occurrences), "aging" (31 occurrences), and "skeletal muscle" (38 occurrences) reflects a gradual expansion in the scope of application—from young, healthy individuals to the prevention of age-related muscle loss and the management of metabolic disorders.

Analysis of nutritional intervention strategies: protein-based supplementation as the dominant approach

As shown in Table 6, nutrition-related keywords are highly concentrated around protein intake and amino

Table 6 Top 20 most frequent terms among author keywords, nutrition-related keywords, and training-related keywords

Author keywords	Freq	Nutrition-related keywords		Freq	Training-related keywords		Freq
Muscle hypertrophy	74	Protein & amino acid-related	Protein	27	Resistance-oriented training	Resistance training	46
Hypertrophy	46		Whey protein	18		Resistance exercise	40
Resistance training	46		Dietary protein	9		Strength training	31
Exercise	43		Whey	7		Resistance exercise training	3
Sarcopenia	42		Casein	3		Weightlifting	4
Resistance exercise	40		Amino acids	21		Weight training	2
Skeletal muscle	38		Essential amino acids	6		Bodybuilding	4
Aging	31		Branched-chain amino acids	4	Training patterns & muscle action types	Exercise training	7
Nutrition	31		Amino acid	3		Training	7
Strength training	31		Leucine	17		Advanced training techniques	1
Muscle mass	27	Supplements-related	Creatine	18		Concentric	3
Protein	27		Protein supplementation	11		Eccentric	3
Strength	26		Supplementation	10		Eccentric training	2
Amino acids	21		Sports nutrition	8		Isometric strength	2
Muscle protein synthesis	19		Supplements	8	Aerobic & general activity	Aerobic exercise	2
Creatine	18		Dietary supplements	4		Aerobic training	1
Protein synthesis	18		Supplement	4		Endurance training	4
Whey protein	18	General Nutrition-related	Nutrition	31		Exercise	43
Leucine	17		Diet	8		Physical activity	2
Body composition	16		Carbohydrate	4		Physical exercise	2

The Table 6 comprises three columns: Author Keywords (left), Nutrition-Related Keywords (middle), and Training-Related Keywords (right). Nutrition- and training-related terms are further classified into semantic subcategories (e.g., Protein & Amino Acid-related, Supplements-related, Resistance-Oriented Training, Training Patterns & Muscle Action Types) to facilitate a more structured understanding of thematic concentrations and the knowledge framework in this research field. "Freq." indicates the number of keyword occurrences across the included studies (n = 411). All terms are extracted from Author Keywords

acid regulation. Terms such as "protein" (27 occurrences), "amino acids" (21 occurrences), "whey protein" (18 occurrences), "leucine" (17 occurrences), and "dietary protein" (9 occurrences) form the core cluster of the "protein–amino acid" family. This reflects the field's longstanding focus on molecular mechanisms related to mTOR signaling, muscle protein synthesis rates, and the anabolic effects of specific nutrients.

Meanwhile, another prominent cluster revolves around dietary supplements, including "creatine" (18 occurrences), "protein supplementation" (11 occurrences), "supplementation" (10 occurrences), "supplements", and "sports nutrition" (each 8 occurrences). These keywords indicate a growing research interest in supplement delivery methods, dosage strategies, and synergistic intervention effects, highlighting a shift from isolated nutrient mechanisms to optimization of intervention protocols and translational applications.

In addition, the high frequency of general terms such as "nutrition" (31 occurrences) and "diet" (8 occurrences) suggests a gradual expansion of the research focus toward overall dietary patterns, nutritional models, and macronutrient distribution strategies. This trend reflects the development of a multi-layered research framework, ranging from molecular-level nutrient regulation to population-level dietary behaviors.

Analysis of training modalities: resistance training as the dominant approach with multidimensional extensions of training variables

As shown in the right column of Table 6, the frequent occurrence of keywords such as "resistance training" (46 occurrences), "resistance exercise" (40 occurrences), and "strength training" (31 occurrences) highlights the widespread use of resistance training as the primary intervention strategy for promoting muscle hypertrophy. This underscores its pivotal role in driving both muscular structural adaptations and metabolic remodeling.

In contrast, appearance-focused terms like "bodybuilding" and "weightlifting" were cited far less frequently (4 occurrences each), suggesting that scholarly interest has largely shifted from aesthetic or competitive domains to the functional mechanisms of training. The emergence of terms such as "eccentric,"

Table 7 Co-occurrence frequency matrix of nutrition-related and training-related keywords (Top 20)

Source_Keyword	Target_Keyword	Weight
Protein	Resistance exercise	11
Nutrition	Exercise training	11
Protein	Resistance training	5
Amino acids	Resistance exercise	5
Diet	Exercise training	5
Supplementation	Strength training	4
Dietary protein	Exercise training	4
Amino acids	Exercise training	3
Creatine kinase	Resistance training	3
Supplementation	Resistance training	3
Protein	Strength training	3
Nutrition	Training	3
Nutrition	Strength training	3
Nutrition	Resistance training	3
Leucine	Resistance training	3
Protein	Exercise training	2
Creatine	Strength training	2
Whey protein	Strength training	2
Diet	Resistance exercise	2
Creatine	Exercise training	2

This table presents the top 20 most frequent co-occurrences between nutrition-related keywords and training-related keywords. Source_Keyword refers to nutrition strategy terms, Target_Keyword refers to training modality terms, and Weight indicates the frequency with which the two keywords co-occur within the same publication—reflecting the strength of their combined research association. This data forms the basis for constructing a two-dimensional "Nutrition × Training" co-occurrence structure, highlighting prevalent matching patterns in intervention strategies within the field

"concentric," and "isometric strength" further indicates a growing emphasis on mode-specific contraction effects and the nuanced influence of different muscle action types, reflecting a trend toward precision modulation of training variables.

Additionally, the presence of terms like "exercise training," "training," and "advanced training techniques" signals the increasing relevance of individualized, periodized, and progressive training models. While less frequently mentioned, "aerobic exercise" and "endurance training" imply a potential role for combined aerobic–resistance interventions, especially in health-promotion contexts.

Overall, resistance training remains the foundational modality in this field, with ongoing exploration into exercise structure, load manipulation, and intervention design. These developments collectively contribute to the theoretical basis for a scientific and systematic muscle hypertrophy training framework.

Co-occurrence network structure: clustering reveals the modular organization of research trajectories

To elucidate the semantic structure among keywords and the evolutionary pathways of research themes, a co-occurrence network was constructed using 52 author keywords with a minimum frequency of 5, as visualized in Fig. 12. The clustering was performed via the VOSviewer algorithm, resulting in the identification of seven distinct semantic modules (Clusters 1–7). The threshold of ≥ 5 occurrences was strategically selected to balance network comprehensiveness and interpretability. On the one hand, this criterion filters out low-frequency, potentially noise-generating terms that could obscure network clarity. On the other hand, aligned with VOSviewer's technical recommendations and established practices in scientometric studies, this threshold ensures that the resulting network remains representative and semantically meaningful—avoiding the pitfalls of under- or over-clustering caused by too few or too many nodes. In the co-occurrence map, node size reflects keyword frequency, edge thickness indicates co-occurrence strength, and node color denotes cluster affiliation. In addition to basic frequency, we further evaluated Total Link Strength (TLS) and Normalized Citations to determine each cluster's functional role and hierarchical status within the broader knowledge structure (see Supplementary Table S1).

Notably, this clustering approach aligns with methodologies adopted in other health-related domains. For example, Azizan et al. (2025) successfully applied co-word and co-citation analyses in Alzheimer's disease research to uncover thematic hotspots and structural hierarchies [35]. Their validation of this method offers strong methodological support and reference value for our use of VOSviewer in semantic clustering within the current study.

Core clusters (structural cohesion and thematic dominance) Cluster 2 (Green) represents the most structurally dense and strongly interconnected module within the co-occurrence network. Anchored by the central term "muscle hypertrophy" (Occurrences = 74, TLS = 150), it is closely associated with high-frequency terms such as "resistance training," "muscle mass," and "creatine," thereby forming the dominant research trajectory centered on "training variables–structural adaptation." This cluster delineates the foundational thematic framework of the field.

Cluster 1 (Red) emphasizes protein-based nutritional interventions and comprises keywords such as "protein" (n = 26), "amino acids" (n = 21, TLS = 66), and "body composition." Characterized by high Total Link Strength and citation performance, this cluster represents a

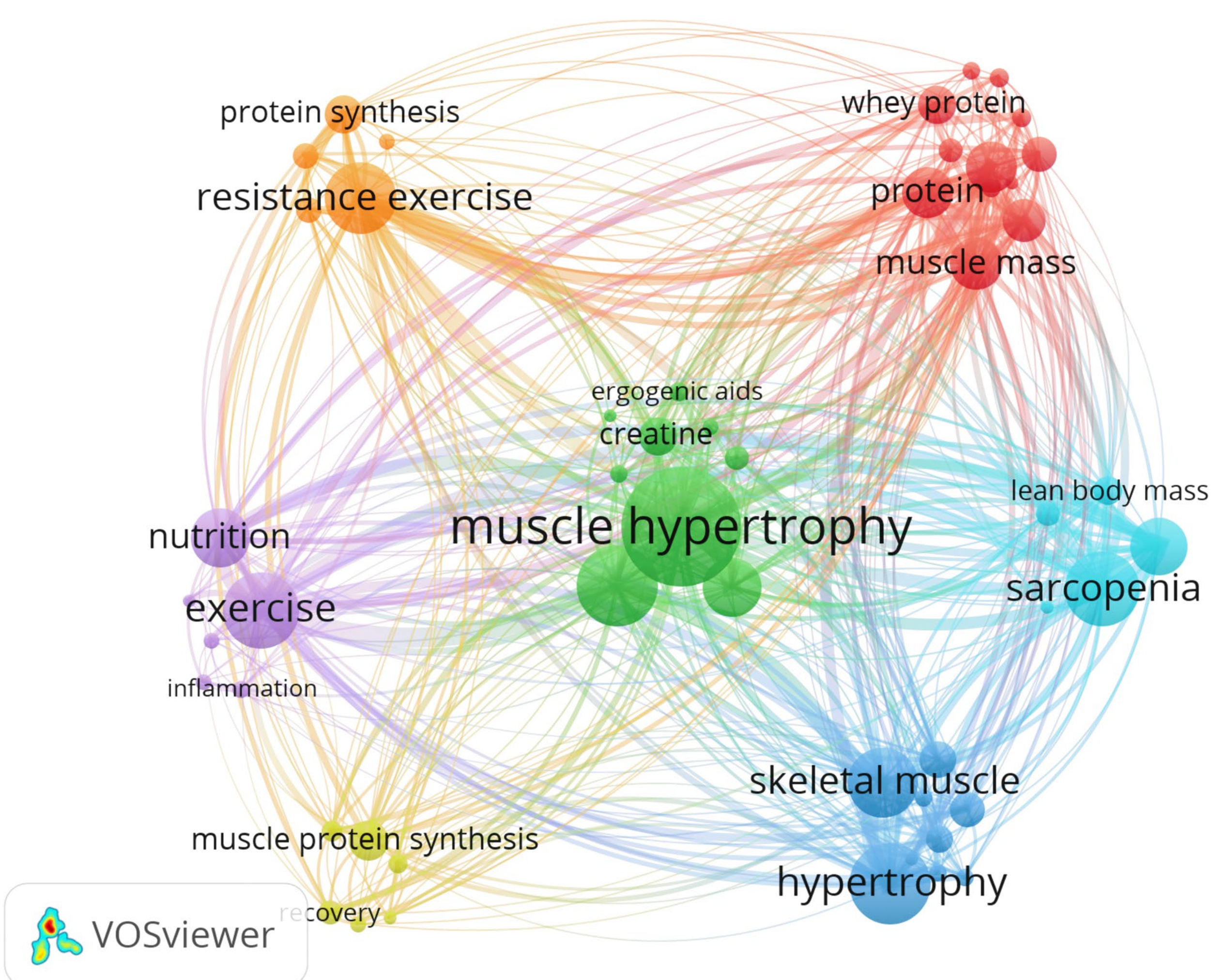


Fig. 12 Co-occurrence network of author keywords (1992–2025) with a minimum frequency threshold of 5, visualized using VOSviewer. Note. This figure includes 52 author keywords. Node size represents keyword frequency, line thickness indicates co-occurrence strength (Total Link Strength, TLS), and colors denote clusters identified by the VOSviewer algorithm (Clusters 1–7). The green, red, and blue clusters represent the core thematic areas, encompassing muscle hypertrophy, resistance training, nutritional interventions, and molecular signaling mechanisms. In contrast, the yellow, purple, cyan, and orange clusters are positioned at the periphery of the network, corresponding to subfields such as protein metabolism, inflammatory adaptation, elderly-specific interventions, and supplement applications. Collectively, the network illustrates a structured knowledge system shaped by the intersection of three primary axes: training, nutrition, and mechanistic research

well-established research line focused on "nutritional supplementation–body composition optimization."

Cluster 3 (Blue) revolves around terms such as "skeletal muscle," "leucine" (Normalized Citations = 1.92), and "hypertrophy," highlighting mechanistic investigations of muscle signaling pathways under nutritional regulation. This cluster functions as a critical bridge linking molecular mechanisms to training-induced adaptations.

Peripheral clusters (semantic independence and looser structure) Cluster 4 (Yellow) centers on protein metabolic pathways and includes keywords such as "protein turnover" (Normalized Citations = 1.89) and "dietary protein." Although this cluster contributes substantial theoretical value, it remains relatively isolated within the network, indicating a supplementary role in mechanistic research.

Cluster 5 (Purple) encompasses terms such as "exercise," "inflammation," and "metabolism." Despite the high linkage strength of "exercise" (TLS = 113), the overall structure of this cluster is more diffuse, suggesting an exploratory trajectory bridging adaptive physiology and immunological responses.

Cluster 6 (Cyan) focuses on age-related interventions, highlighting terms such as "sarcopenia," "aging," and "elderly." While demonstrating considerable citation influence (e.g., “elderly” Normalized Citations = 1.54), this cluster is located at the periphery of the network, underscoring its semantic independence and strong application-oriented nature.

Cluster 7 (Orange) bridges practical applications and mechanistic research, centered on terms such as “resistance exercise” and “protein supplementation.” As a transitional cluster, it reflects the intersection between experimental protocols and applied supplementation strategies.

Overall, the network structure exhibits a distinct three-tiered pattern comprising core, transitional, and peripheral layers. The core zone, anchored around muscle hypertrophy, integrates training variables and nutritional interventions into a tightly interwoven thematic trajectory. In contrast, the peripheral zones encompass topics such as protein metabolism, immune adaptation, and aging-related applications, highlighting the structural complexity and multidisciplinary nature of research in this domain.

It is worth noting that although previous studies have employed scientometric approaches to investigate themes related to resistance training or sports nutrition, they often lacked structural or integrative depth. For instance, Zeng et al. [13] focused on protein supplementation and resistance training in the context of sarcopenia among older adults but did not clearly define the underlying keyword structure. Podrigalo et al. [36] conducted a Scientometric analysis on strength sports, yet failed to incorporate a nutritional perspective. Xu et al. [37] identified “exercise patterns” and “nutritional strategies” as frequent terms, but their study primarily centered on exercise-induced injury and did not systematically examine the synergistic pathways between training modalities and nutritional interventions, nor did it utilize structured clustering or semantic stratification. In contrast, the present study is the first to adopt “nutritional intervention × resistance training” as dual-core dimensions, constructing a co-occurrence matrix and a seven-cluster network to comprehensively map the knowledge evolution from mechanistic inquiry to applied intervention, thereby addressing a critical gap in cross-dimensional integration within the field.

“Nutrition × Training” co-occurrence matrix: highly concentrated pairing patterns

To further investigate the frequency and patterns in the combinations of nutritional strategies and training modalities, a “Nutrition × Training” author keyword co-occurrence matrix was constructed (Table 7), from which the top 20 most frequent pairings were extracted for analysis.

The results indicate that the most commonly co-occurring pairs are “protein × resistance exercise” and “nutrition × exercise training,” each appearing 11 times. These pairings suggest that protein intake combined with various forms of resistance-based training constitutes the dominant research configuration. Subsequent combinations include “amino acids × resistance exercise” (5 occurrences), “diet × exercise training” (5 occurrences), and “supplementation × strength training” (4 occurrences).

Although pairings such as “creatine × strength training” and “whey protein × strength training” appear less frequently (2 occurrences each), they exhibit stable linkages within the structural network, indicating their potential relevance for specific populations or targeted outcomes (e.g., recovery enhancement or power development).

Overall, the combination of “protein/amino acids + resistance training” emerges as the most frequently adopted intervention model in current research. Its high frequency reflects not only a concentrated research focus but also its broad applicability and strong experimental controllability in practice-oriented settings.

Keyword type differentiation analysis: author keywords vs. keywords plus

To further examine the distinctions between different keyword systems in identifying research themes and constructing knowledge structures, this study extracted both Author Keywords (n = 800) and Keywords Plus (n = 1157) from the Web of Science database. Frequency statistics, word cloud visualizations, and VOSviewer clustering maps were employed to conduct a comparative analysis, as shown in Fig. 13a–d.

Figure 13a illustrates the top 20 most frequently occurring author keywords, presented through a combined bar chart and word cloud. Terms such as "muscle hypertrophy" (n = 74), "resistance training," "protein," "leucine," and "sarcopenia" appear with high frequency, highlighting the semantic concentration of author keywords around the core axis of “resistance training–muscle adaptation–nutritional regulation.”

Figure 13b visualizes the co-occurrence network constructed from 52 high-frequency author keywords (frequency ≥ 5), with clustering analysis performed using VOSviewer. Seven semantic clusters were identified, corresponding to the following thematic areas: (1) nutritional supplementation and body composition regulation, (2) muscle hypertrophy and training variables, (3) molecular mechanisms and signal transduction, (4) protein metabolism and dietary strategies, (5) training adaptation and inflammatory responses, (6) age-related muscle decline, and (7) translational applications in practice-oriented contexts.

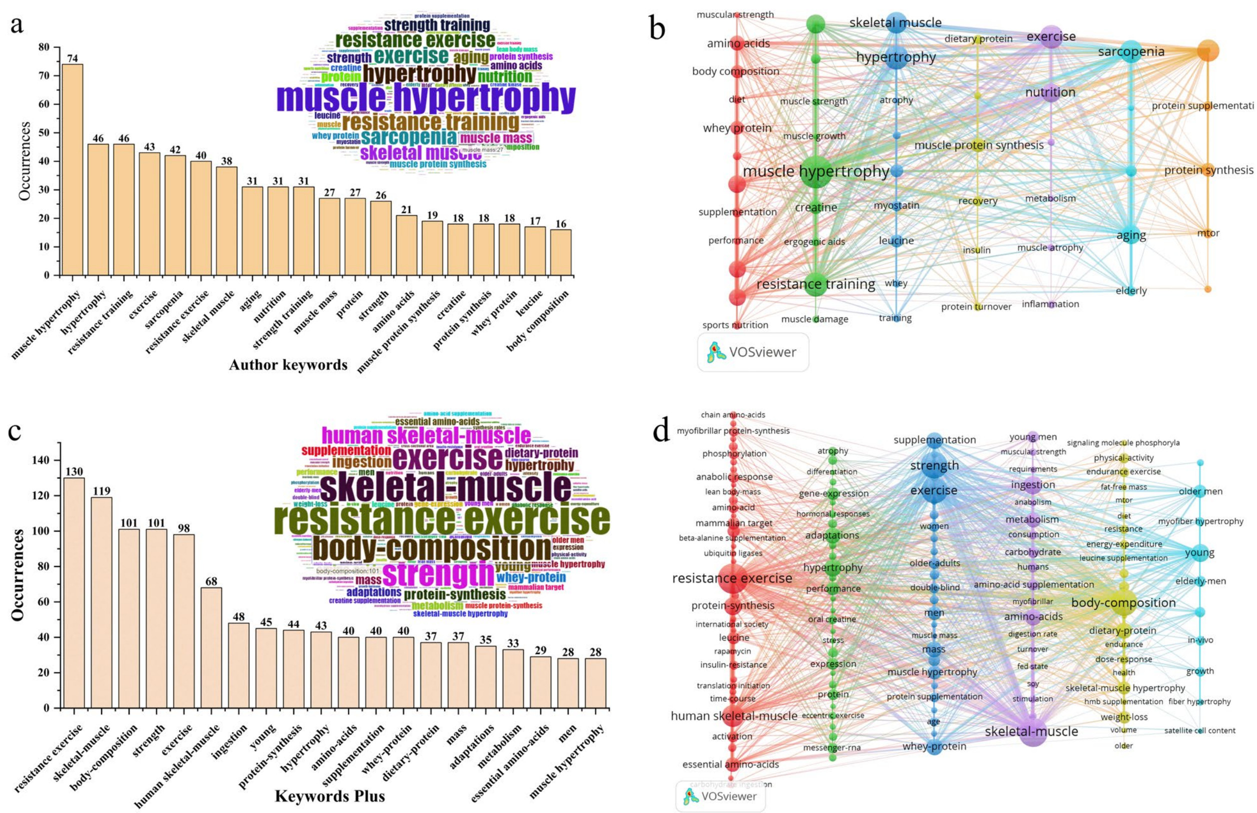


Fig. 13 Comparative Visualization of Author Keywords and Keywords Plus. Note. (a) Top 20 most frequent author keywords and corresponding word cloud; (b) Co-occurrence clustering network of author keywords (n = 52, frequency ≥ 5); (c) Top 20 most frequent Keywords Plus terms and word cloud; (d) Co-occurrence clustering network of Keywords Plus (n = 149, frequency ≥ 5). Colors indicate different clustering modules, and the thickness of the links represents the co-occurrence strength between terms

Figure 13c presents the top 20 most frequent Keywords Plus terms using a similar approach, combining a bar chart and word cloud. Frequently occurring terms such as "resistance exercise" (n = 130), "skeletal muscle" (n = 119), "body composition," "strength," and "exercise" indicate their broad representation in the citation-based indexing system.

Figure 13d further constructs a co-occurrence network based on 149 Keywords Plus terms with a minimum frequency of five, with VOSviewer used to identify six major clustering structures. The resulting thematic domains include: (1) mechanisms of protein synthesis, (2) training-induced adaptations, (3) interventions for age-related muscle decline, (4) body composition regulation, (5) protein nutrition and metabolism, and (6) fundamental research on signaling pathways.

In summary, the visualizations reveal that author keywords offer greater thematic specificity and clearer hierarchical organization, making them more suitable for uncovering core research objectives and mechanistic pathways. Conversely, Keywords Plus serves as a useful complement for mapping structural breadth and citation linkages. Accordingly, this study adopts author keywords as the sole input for co-occurrence clustering analysis, while Keywords Plus is employed for comparative validation and structural cross-referencing, ensuring the semantic accuracy, theoretical coherence, and methodological reproducibility of the results.

Previous studies have highlighted that author-assigned keywords primarily serve as semantic indicators of the research theme and research object within academic publications, functioning as essential anchors for content identification and information retrieval processes [38]. As pivotal nodes linking research content with academic discourse, keywords play a foundational role in literature search, scholarly communication, expert matching, and evidence synthesis. The accurate and standardized selection of keywords not only enhances a paper's discoverability and citation potential but also directly influences its impact within the academic dissemination system [39].

Empirical evidence further suggests that while Keywords Plus perform comparably to author keywords in delineating the broader knowledge structure of a discipline, they tend to be less precise in reflecting the specific content of individual articles [40]. According to Lu et al. [41], the selection of author keywords represents a synthesis of the author's understanding of the article's content, cited literature, and domain-specific terminology. Their findings show that 56.7% of author keywords are derived from titles and abstracts, 41.6% from references, and 56.1% overlap with high-frequency field-specific terms—demonstrating a high degree of accuracy and representativeness in conveying core research themes. Overall, keywords are crucial to enhancing the visibility and retrieval efficiency of scientific publications. Therefore, keyword selection should be both precise and standardized to optimize discoverability and citation performance [42].

Structural patterns of variable combinations and keyword co-occurrence

To further identify the core variable pairings within the tripartite research axis of "nutritional strategies—training modalities—muscle-related outcomes", this study draws upon the author keyword co-occurrence network (Fig. 12) and the cluster results table (Appendix Table S1). The analysis is conducted across three dimensions: (1) distribution of high-frequency variables, (2) typical combination pathways, and (3) clustering of knowledge structures. The aim is to determine whether a stable research model has emerged in this field, and whether a clear distinction exists between mechanism-oriented studies and application-focused intervention research.

Distribution and functional classification of high-frequency keywords

Based on the keyword clustering data (see Fig. 12 and Appendix Table S1), a total of seven clusters were identified, involving 52 keywords with a frequency of occurrence ≥ 5. These high-frequency terms can be broadly categorized into the following three types:

Training-related variables: Keywords such as resistance training (46 occurrences), strength training (31 occurrences), exercise (43 occurrences), and resistance exercise (40 occurrences) demonstrate that resistance-based modalities remain the primary research thread in this domain.

Nutritional intervention variables: Terms like protein (26 occurrences), amino acids (21 occurrences), whey protein (18 occurrences), creatine (18 occurrences), and leucine (17 occurrences) indicate the extensive use of protein-related strategies in existing studies.

Structural/mechanistic outcome variables: Terms such as muscle hypertrophy [73], muscle mass (27 occurrences), muscle protein synthesis (19 occurrences), and mTOR (11 occurrences) emphasize muscle anabolism and hypertrophy as the primary outcome measures.

Collectively, these high-frequency variables constitute the semantic foundation of current research, serving as the basis for subsequent cluster segmentation and the identification of triadic research pathways.

Triadic variable combinations: representative pathways and stable pairings

To further elucidate the thematic stability and structural logic within the "Nutrition × Training × Structural/Mechanistic" triadic pathways, we analyzed the keyword co-occurrence network ($n = 52$, frequency ≥ 5) constructed using VOSviewer and identified seven clusters (Cluster 1–7) as shown in Fig. 12. Through co-clustering and network linkage analysis, five stable co-occurring triadic combinations were identified, each representing a representative research pathway in this field:

Cluster 1 (Red): A typical combination is protein + strength + muscle mass, which emphasizes the synergistic effect of protein intake and resistance training on muscle volume enhancement. This represents a classical application-oriented model and includes the largest number of keywords, such as "protein," "amino acids," "body composition," "strength," "diet," "sports nutrition," and "supplementation." These terms collectively reflect the foundational research focus on how macronutrients (e.g., protein, amino acids, supplements) combined with resistance training influence body composition and strength development. Notably, "amino acids" (Occurrences = 21, TLS = 66) and "body composition" (Occurrences = 16, Norm. Citations = 1.22) demonstrate strong citation performance. This pathway supports individualized nutrition-training strategies widely used in muscle-building programs, general fitness guidance, and athletic conditioning.

Cluster 2 (Green): Centered around resistance training + creatine + muscle hypertrophy, this combination represents supplement-focused research aimed at enhancing training-induced outcomes. Keywords include "muscle hypertrophy," "resistance training," "creatine," "muscle mass," and "strength training." This cluster highlights mechanisms of muscle hypertrophy, supplement-based performance enhancement, and the optimization of training variables. "Muscle hypertrophy" is the most frequently occurring term across the entire network (Occurrences = 74, TLS = 150), underscoring its centrality to the field.

Cluster 4 (Purple): Featuring combinations such as dietary protein + amino acids + muscle protein synthesis, this cluster emphasizes metabolic regulation and the influence of nutritional molecules on anabolic signaling. Core terms include "muscle protein synthesis," "protein turnover," "dietary protein," and "insulin," reflecting research into the dynamic processes of protein metabolism and the metabolic pathways modulated by various protein types. Although "protein turnover" appears only eight times, its high normalized citation rate (Norm. Citations = 1.89) signifies its representative value in mechanistic research.

Cluster 6 (Cyan): This includes combinations such as exercise + dietary protein + sarcopenia, directly addressing the growing public health concern of age-related muscle decline. It represents a translational pathway from research to clinical practice, with practical implications for the development of nutritional guidelines, home-based training prescriptions, and community health services for older adults. Terms such as "sarcopenia" (Occurrences = 42, Norm. Citations = 1.46) and "elderly" (Norm. Citations = 1.54) exhibit high citation intensity, highlighting the relevance of this cluster in the context of healthy aging.

Cluster 7 (Orange): Represented by resistance exercise + protein supplementation + mTOR, this cluster bridges nutritional signaling pathways and exercise-induced anabolic activation mechanisms. It includes terms such as "resistance exercise," "protein supplementation," "protein synthesis," and "skeletal muscle hypertrophy." Positioned at the interface between basic mechanistic studies and applied research, this pathway connects signal transduction with nutritional intervention. It is representative of multi-pathway integration aimed at translating mechanistic insights into functional outcomes, thereby facilitating the development of precision nutrition and individualized training regimens.

These stable triadic combinations not only recur frequently across the literature but also form densely connected nodes within the co-occurrence network. This pattern suggests the establishment of distinct thematic trajectories and structurally stable research subdomains within the broader field.

Modular differentiation of research orientations revealed through clustering

As observed from the clustering map generated by VOSviewer (Fig. 12) and thematic clusters extracted from Appendix Table S1, the author keyword clusters exhibit a clear differentiation between mechanistic and application-oriented research (see Table 8):

This modular pattern suggests that current research is no longer characterized by the isolated accumulation of variables, but rather by the formation of semantically cohesive, logically connected, and thematically coherent knowledge structures across nutritional strategies, training modalities, and physiological mechanisms. The findings of this section confirm that research on muscle adaptation under combined nutritional and training interventions has developed multiple stable triadic combinations (training × nutrition × structure). The clustering structures reveal a distinct semantic bifurcation between mechanism-driven and application-focused studies. The visual clustering output from VOSviewer and the supporting Appendix tables facilitate the thematic identification and theoretical structuring of research hotspots, laying a solid foundation for future exploration of topic evolution and knowledge expansion in this domain.

Thematic evolution: transition from mechanism-oriented to application-oriented research

To systematically trace the evolutionary trajectory of research on muscle health and nutrition-training interventions, this study integrates the keyword burst detection map generated by CiteSpace (Fig. 14) and the thematic evolution pathway produced by Bibliometrix (Fig. 15). Together, these visualizations provide a comprehensive overview of the temporal development of author keywords from 1992 to 2025, with a particular focus on how the research paradigm has shifted—from

Table 8 Author keyword clusters and thematic interpretation (based on co-occurrence network, frequency ≥ 5)

Cluster ID	Representative keywords	Thematic category	Research orientation description
Cluster 1	Protein, amino acids, whey protein	Nutritional Metabolic Regulation	Focuses on protein intake and metabolic interventions; application-oriented pathway
Cluster 2	Muscle hypertrophy, resistance training	Muscle Structural Effects	Emphasizes intervention outcomes such as muscle hypertrophy and strength performance
Cluster 4	Muscle protein synthesis, mTOR	Anabolic Signaling Mechanisms	Focuses on molecular mechanisms and explores the synergistic pathways of training and nutrition
Cluster 6	Sarcopenia, aging, dietary protein	Elderly Intervention Strategies	Emphasizes functional maintenance and recovery in older populations
Cluster 7	Resistance exercise, protein supplementation	Integration of Mechanistic and Applied Research	Bridges the relationships among training stimuli, nutritional supplementation, and signaling activation

This table summarizes the representative clusters generated from the co-occurrence network of author keywords (n = 52, frequency ≥ 5), based on VOSviewer analysis. Each cluster represents a distinct thematic focus within the research field of nutritional interventions and resistance training related to muscle hypertrophy. Thematic categories were manually interpreted and categorized according to dominant keywords and network position, and research orientations were summarized based on semantic relevance and cited literature trends. Cluster IDs correspond to the color-coded modules presented in Fig. 12

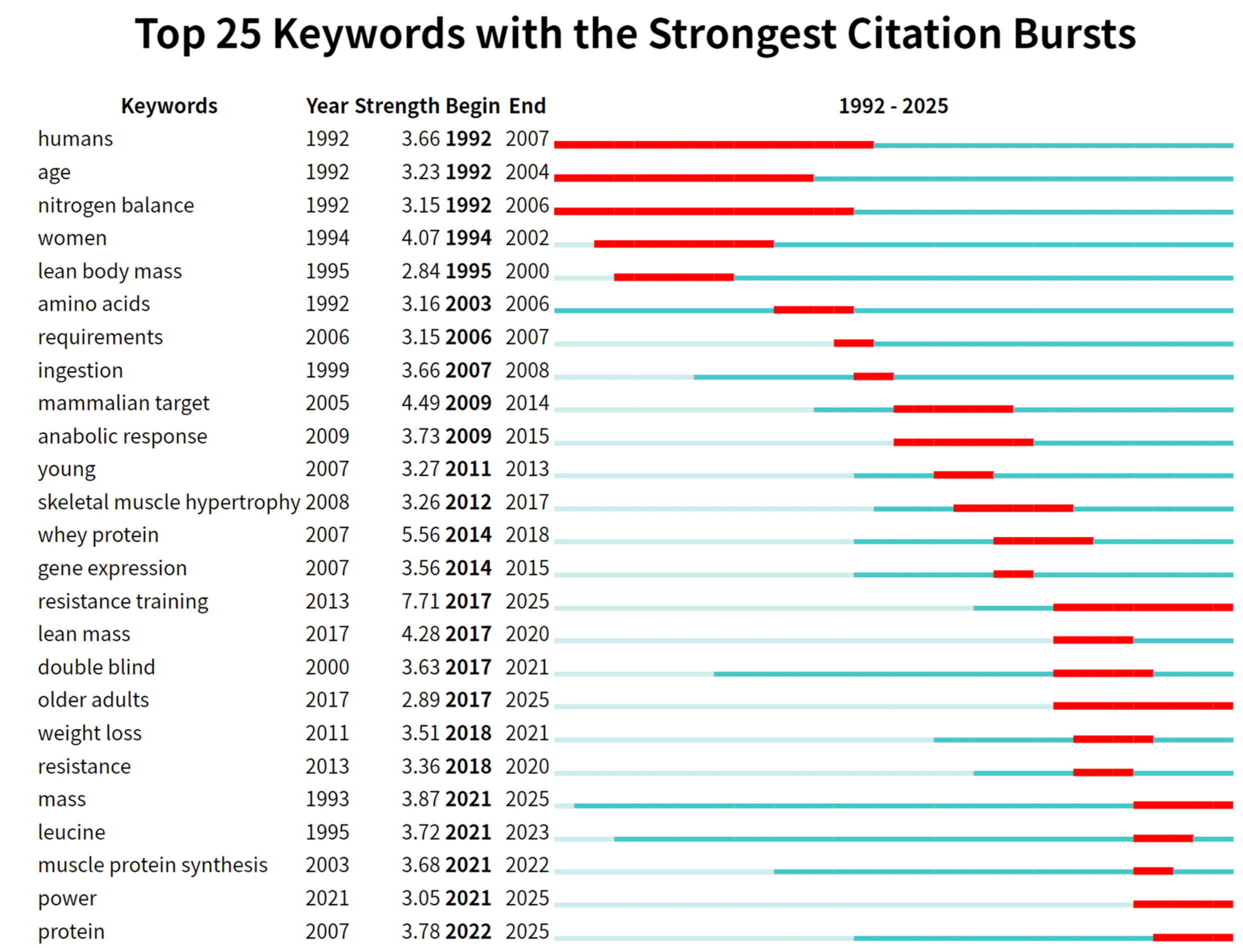


Fig. 14 Top 25 Burst Keywords. Note: This figure was generated using burst detection analysis in CiteSpace, covering the period from 1992 to 2025. Data sources include article titles, abstracts, Author Keywords, and Keywords Plus. The burst detection model was configured with a γ value of 0.79 and a minimum burst duration of two years. Red segments indicate periods during which specific keywords experienced significant citation bursts, reflecting concentrated surges of research interest in particular topics at different time points

mechanistic molecular investigations toward real-world interventions and clinical applications.

As illustrated in Fig. 14, the early period (1992–2010) was characterized by the emergence of high-frequency burst keywords such as mammalian target (mTOR), anabolic response, gene expression, nitrogen balance, amino acids, and protein synthesis. These terms reflect the research community's primary focus on the molecular signaling pathways and metabolic regulation underlying protein synthesis in response to training and nutritional stimuli. Investigations during this period were predominantly mechanistic, relying on laboratory models and short-term biomarkers.

For instance, Yarasheski et al. [43] distinguished between systemic and localized regulation by analyzing protein synthesis rates under combined growth hormone administration and resistance training. Wang et al. [44] documented structural changes in muscle fiber types among women following resistance training, providing morphological evidence for skeletal muscle plasticity. Campbell et al. [45] were among the first to involve older adults in protein intervention studies, exploring how varying protein intakes influenced nitrogen retention—marking an early shift from pure mechanism to applied perspectives. Subsequently, Slater and Jenkins [46] examined the anti-catabolic potential of HMB, suggesting a translational link between amino acid metabolism and practical interventions. Bamman et al. [47] and Deldicque et al. [48] further elucidated the role of localized IGF-I, mTOR, and AMPK signaling in mediating adaptive responses to training stimuli. Kraemer and Ratamess [49] emphasized the significance of acute hormonal fluctuations induced by resistance exercise in regulating muscle remodeling, thereby promoting the integration of mechanical load, signaling activation, and muscle adaptation into a cohesive research framework.

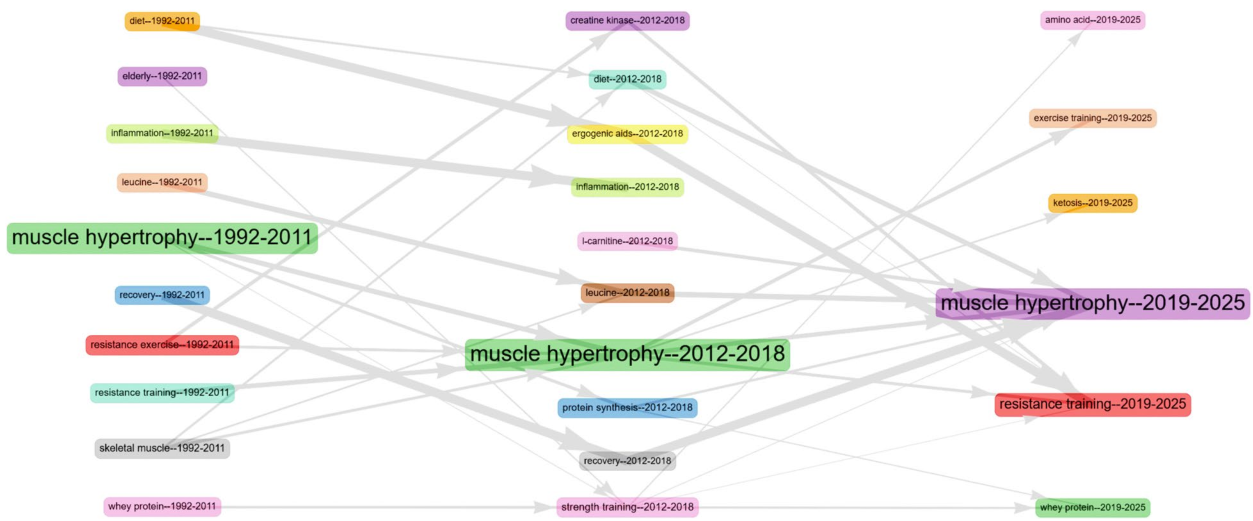


Fig. 15 Thematic Evolution Map Based on Author Keywords. Note. This figure was generated using Bibliometrix (R/Biblioshiny), with Author Keywords as the primary unit of analysis. The research timeline was divided into three periods (1992–2010, 2011–2018, and 2019–2025), and a three-phase evolution map was constructed to visualize the continuity and transformation of high-frequency research themes. Different colors indicate distinct thematic clusters, while arrows represent inheritance and derivation relationships among topics. The map highlights the evolutionary trajectory of the field, transitioning from foundational mechanistic studies to intervention-oriented and application-driven research frameworks

As this mechanistic foundation solidified, some studies began bridging molecular mechanisms with specific nutritional strategies. Notably, Hulmi et al. [50] demonstrated the significant role of whey protein in enhancing muscle protein synthesis in the context of resistance training, highlighting the critical importance of nutrient timing. This marked a transitional phase in the field—from a focus on mechanistic modeling to the early development of applied intervention pathways. As depicted in the thematic evolution map (Fig. 15), "muscle hypertrophy" during this stage was closely linked to keywords such as "protein synthesis" and "leucine," underscoring the molecular regulatory focus that defined the research paradigm of this era.

In the intermediate stage (2011–2018), research gradually transitioned from molecular mechanisms to validating the efficacy of interventions under real-world training conditions. Emerging burst keywords such as muscle protein synthesis, whey protein, sarcopenia, and physical performance signaled a shift in research populations—from healthy young adults to frail older individuals—and a parallel shift in focus from intracellular signaling to structural outcome evaluations, including lean body mass and muscular strength. Phillips and Van Loon [30] emphasized that protein intake functions not only as a substrate for synthesis but also plays a signaling regulatory role through leucine, advocating an intake of 1.3–1.8 g/kg/day with a focus on post-exercise timing. Moore et al. [51] further confirmed that resistance training combined with protein supplementation significantly prolongs activation of the mTOR and MAPK signaling pathways, closely paralleling the extended duration of MPS responses. Joy et al. [52] demonstrated comparable hypertrophic effects between whey and plant-based proteins, providing empirical support for diversified protein sourcing. Phillips [31] also highlighted the importance of protein absorption rates and amino acid profiles in modulating training adaptations, advocating for mechanistic insights to inform nutritional strategies. Damas et al. [53] noted that short-term changes in MPS do not always correlate with long-term hypertrophy, calling for the integration of extended MyoPS measurements and structural muscle assessments. Stokes et al. [54] proposed increasing protein intake to 2.3–3.1 g/kg/day in energy-restricted scenarios to preserve lean mass. As shown in the thematic evolution map (Fig. 15), muscle hypertrophy during this phase increasingly clustered with keywords such as muscle protein synthesis, whey protein, and sarcopenia, indicating that mechanistic findings had begun to translate into quantifiable intervention outcomes.

In the most recent phase (2019–2025), the research trend has become increasingly practice-oriented. As shown in Fig. 14, burst keywords such as resistance training, older adults, exercise training, dietary protein, protein, and lean mass indicate a comprehensive shift from laboratory-based models to real-world interventions and the refinement of precision nutrition strategies. Moore [55] proposed that relative protein intake

(0.31 g/kg per meal) is more operationally feasible than fixed-dose strategies, underscoring the importance of nutritional efficiency. Endo et al. [56] highlighted that combining protein intake with supplements such as creatine could improve anabolic resistance in older adults. However, Roschel et al. [57], in a randomized controlled trial involving frail individuals, reported no additional hypertrophic benefit from whey, leucine, or creatine supplementation beyond that of resistance training alone, emphasizing the primacy of exercise as the foundational intervention. A systematic review by Kirwan et al. [58] confirmed that protein supplementation yields significant improvements in lean mass and handgrip strength only when combined with exercise, reinforcing the synergistic necessity of the "training + protein" paradigm. Bagheri et al. [59] further demonstrated that high protein intake effectively promotes muscle mass and strength in older veterans without adverse safety outcomes. Paoli et al. [12] extended the nutritional perspective by proposing omega-3 fatty acids, antioxidants, and probiotics as complementary factors that could augment the effects of protein-based interventions, reflecting a systems-based approach to nutritional support. Tang et al. [60] systematically summarized the chemical properties of whey protein, its leucine content, and mTOR activation potential, recommending an intake of 20–25 g per serving for optimal effects. Rathmacher et al. [61], representing the International Society of Sports Nutrition (ISSN), emphasized the dual mechanism of β-hydroxy-β-methylbutyrate (HMB)—promoting synthesis and inhibiting breakdown—demonstrating its efficacy in improving muscle quality in elderly and rehabilitative populations, thereby contributing to an evidence-based, outcome-oriented intervention model.

As further illustrated in the thematic evolution map (Fig. 15), muscle hypertrophy has remained the core topic throughout all three periods. The associated keywords evolved from "protein synthesis" and "leucine" in the early phase, to "muscle protein synthesis" and "whey protein" in the mid-phase, and more recently to "resistance training," "older adults," and "dietary protein" in the current phase. This progression vividly reflects the field's shift from mechanistic exploration and intervention validation to the adoption of adaptive strategies for diverse, real-world populations.

In summary, over the past three decades, this research domain has undergone a profound transformation—from laboratory-based mechanistic models to evidence-based nutritional and training strategies designed for older adults and special populations. A practical paradigm centered on "dietary protein + resistance training" has emerged, reflecting a more mature scientific framework that increasingly emphasizes translational efficacy and real-world applicability.

Key findings overview

Based on the findings from Sects. "Main information" to "Thematic evolution: transition from mechanism-oriented to application-oriented research", this study highlights several key characteristics and critical insights into the field of nutritional interventions and resistance training for muscle hypertrophy:

(1) *Stable structural foundation with modest growth* Since 1992, the field has demonstrated a steady upward trajectory, with an average annual growth rate of 3.39%. Although the expansion is continuous, the overall growth remains moderate, indicating a solid research foundation without explosive development.
(2) *High thematic concentration on protein and classical training variables* The keyword co-occurrence network reveals a dominant presence of high-frequency terms such as *protein*, *resistance training*, and *muscle hypertrophy*, reflecting a central research trajectory focused on the interplay between protein intake, resistance training, and muscle outcomes. Most studies remain anchored in traditional variables, such as protein types, timing of intake, and training intensity.
(3) *Clustering divergence between mechanistic and applied research* Keyword clustering analysis indicates a bifurcated structure characterized by a "mechanism-to-application" dichotomy. On one hand, clusters centered around *mTOR* and *protein synthesis* outline a clear pathway of molecular signaling research. On the other hand, clusters comprising *sarcopenia* and *older adults* reflect an applied, population-oriented research trajectory. While partial overlap exists, these dimensions remain insufficiently integrated, suggesting the need for a more coherent linkage between molecular mechanisms and functional outcomes in future research.
(4) *Thematic evolution follows a "mechanism–validation–application" progression* Citation burst analysis and thematic pathway mapping jointly illustrate a progressive shift in research paradigms—from early-stage investigations of metabolic mechanisms, to mid-stage validation of intervention strategies, and finally to late-stage applications targeting older populations. This reflects a maturing scientific logic within muscle hypertrophy research under the nutrition-training framework, with increasing alignment toward real-world health needs.

Table 9 Summary of key research gaps and future recommendations in nutritional and exercise interventions

Identified research gap	Problem description	Recommended future research
Underrepresentation of females and non-Western populations	Existing studies predominantly sample male and Western participants, with limited investigation into sex-specific responses or cultural dietary adaptations	Future studies should recruit demographically balanced samples across sex and region; analyses should include hormonal fluctuations and cultural dietary contexts
Insufficient focus on recovery and metabolic health indicators	Most research centers on muscle mass and strength outcomes, while recovery rate and metabolic health metrics remain underexplored	Expand recovery-focused nutritional strategies (e.g., anti-inflammatory and antioxidant approaches); incorporate clinical markers such as HbA1c and insulin sensitivity to evaluate metabolic adaptations
Lack of alignment between nutritional periodization and female physiological rhythms	Intervention designs rarely integrate dietary periodization synchronized with the menstrual cycle, overlooking sex-specific timing needs	Integrate periodized nutrition with training cycles; examine menstrual phase–specific nutritional adaptations to optimize intervention effectiveness in women
Limited development of individualized intervention strategies (precision nutrition/training)	Most protocols apply uniform intervention designs, neglecting interindividual variability in genetics, nutrient metabolism, and exercise responsiveness	Advance nutrigenomic and personalized response studies; develop adaptive intervention frameworks incorporating AI-based feedback and individualized training-nutrition integration

This table outlines critical gaps in current research related to sex and cultural representation, recovery and metabolic health indicators, nutritional periodization, and personalized intervention strategies. For each gap, specific issues and proposed directions for future studies are provided to guide improved design and inclusivity in nutritional and exercise science

(5) *Structural imbalance in regional and population representation* Despite approximately 30% of publications involving international collaboration, the research landscape remains heavily dominated by institutions in Europe and North America. Asia, Africa, and Latin America exhibit significantly lower publication counts and citation impact. Although China ranks among the most productive countries, its average citation rate remains comparatively low, indicating underrealized global influence. Furthermore, female participants and non-Western populations are still markedly underrepresented. Critical variables such as sex differences, cultural context, and dietary patterns have yet to be systematically addressed, limiting the generalizability and external validity of current findings.

Collectively, these findings not only map the knowledge structure and developmental pathways of the field but also underscore the urgent need to promote mechanism-to-application integration, increase the inclusion of underrepresented populations, and diversify intervention variables to facilitate broader health translation.

Research gaps and future directions

Although the field has made substantial progress, our scientometric mapping—encompassing research productivity, keyword co-occurrence, burst term dynamics, and peripheral cluster identification—has revealed several underexplored areas (see Table 9). These research gaps were not derived from conventional narrative reviews, but rather emerged from a structured, data-driven visual analysis and network-based variable mining. As such, they represent theoretical discontinuities and practical blind spots that warrant targeted investigation. This approach provides an empirically grounded framework to guide future research with greater precision and contextual relevance.

Underrepresented populations (women and non-western groups) Current muscle hypertrophy research, especially studies combining nutrition and resistance training, has a notable bias toward male subjects and Western populations. Women have historically been underrepresented in exercise science studies [62], which limits insights into sex-specific responses and effective strategies for female trainees. Although evidence suggests that females can achieve hypertrophy and strength gains similar to males under equivalent training protocols [63], relatively few studies explicitly focus on female hormonal influences (e.g., menstrual cycle phase) or tailor interventions to women [64, 65]. Addressing this gap is crucial, as recent work indicates the menstrual cycle phase has minimal impact on strength gains when women follow well-designed programs [65, 66], yet training and nutrition guidelines could be refined to women's physiology (for instance, considering iron or calcium needs around menses or leveraging high-estrogen phases for intense training).

Additionally, our Scientometric analysis reveals a geographic concentration of research in North America, Western Europe, and parts of the Asia–Pacific, with limited visibility from Asian, African, and Latin American countries (see Sect. "National research output and scientific impact"; Table 1). Genetic, dietary, and cultural differences might influence training-nutrition outcomes (for example, habitual protein intake tends to be lower in some Asian diets, which could affect supplementation needs). Future research should strive for greater inclusion of women (ensuring roughly equal representation where possible [62, 67]) and participants from diverse ethnic and regional backgrounds. Such efforts will improve the generalizability of findings and could uncover population-specific factors (e.g., differential lactose tolerance affecting whey protein use in various groups) that inform personalized recommendations. Initiatives to increase female participation and leadership in sports science research are underway [62], and these should be bolstered by funding agencies and research designs that mandate or encourage diversity.

Recovery and metabolic health outcomes Much of the hypertrophy research focuses on muscle size and strength endpoints, but comparatively less attention has been paid to recovery kinetics and metabolic health indicators. Our cluster analysis noted "recovery" as a keyword associated with an emerging applied research cluster (yellow cluster) but still not among the top recurring terms. Optimizing recovery (between sessions and post-exercise) is essential for sustainable training progress, yet nutritional strategies specifically targeting recovery (beyond protein for MPS) are under-represented. Some nutritional compounds like tart cherry juice or omega-3 fatty acids show promise in reducing muscle soreness and inflammation [68], but evidence is limited to specific contexts and more research is needed to generalize these findings. Future studies could explore, for example, periodized antioxidant or anti-inflammatory nutrient intake for individuals undergoing high-frequency training, or the role of sleep-related nutrition (like pre-sleep protein or collagen) in muscle repair. In addition, although early research was very metabolism-centric (examining signaling pathways, enzyme activation, etc.), there is opportunity to re-connect with metabolic health outcomes in applied studies. Resistance training is known to improve metabolic health markers such as insulin sensitivity and glycemic control [69], and when combined with nutritional interventions (high-protein diets, creatine which may affect glucose uptake, etc.), the synergy could confer broader health benefits. Investigating outcomes like changes in HbA1c, lipid profiles, or inflammatory markers in hypertrophy-oriented programs would broaden the impact of this field and intersect with public health (e.g., using muscle-building programs to combat type 2 diabetes or obesity) [70]. Such studies would also integrate the "mechanistic" and "applied" clusters by linking molecular outcomes to whole-body health metrics.

Neglected factors: nutritional periodization and cyclical strategies Our analysis hints at a lack of studies on nutritional periodization—the deliberate manipulation of diet across training cycles. Most interventions maintain consistent nutrition throughout study periods, yet athletes in practice often use cyclic approaches (bulking and cutting phases, or aligning higher protein/calorie intake with heavy training cycles). The absence of "periodization" or "cycle" as common keywords (aside from "aging" or "recovery" contexts) suggests this is an area ripe for exploration. A position stand highlighted the need for research on implementing periodized nutrition plans for strength athletes [71]. Future research could examine, for instance, the effects of alternating high-protein phases with maintenance phases on long-term hypertrophy, or how cyclic carbohydrate strategies (e.g., carb cycling or timed high-carb refeeds) might influence training performance and muscle gains.

Another overlooked aspect is the influence of physiological cycles—particularly in women. The term "menstrual cycle" is virtually absent in the co-occurrence analysis, yet questions remain about whether training and nutrition should be adjusted across menstrual phases to optimize hypertrophy (current evidence suggests strength performance is not drastically affected by cycle phase [65], but more chronic adaptation studies are needed). Research integrating female hormonal cycles or oral contraceptive status into hypertrophy studies (and corresponding nutritional support, like higher caloric intake during luteal phase if metabolic rate is increased) could provide practical guidelines for female athletes, addressing both the female research gap and cyclical nutrition concept [66, 72, 73]. Recent literature has also highlighted persistent evidence gaps concerning key health issues in women, despite the growing participation of female athletes. Topics such as menstrual cycle regulation, pregnancy, and postpartum recovery remain underrepresented in sports science research. Systematic reviews in female-specific disciplines, including women's cricket, have underscored this shortfall [74, 75]. Moreover, two recent systematic reviews emphasized the efficacy of physical activity in alleviating premenstrual syndrome (PMS), demonstrating that various exercise modalities—including aerobic training, yoga, and resistance training—can significantly reduce fatigue, improve mood, and relieve somatic symptoms. These findings support the development of periodized interventions and sex-specific training strategies for women [76, 77]. In men, investigating circadian timing (e.g., morning vs evening training combined with feeding) might also yield insights—some evidence indicates that training at different times of day can interact with nutrient timing to affect muscle anabolism [78–80]. Overall, incorporating periodization—both in training and diet—reflects a more realistic scenario for athletes and could enhance the ecological validity of research findings [71, 81].

Lack of individualized interventions (precision nutrition and training) Perhaps one of the most significant future directions is the move toward personalized or precision strategies. Our analysis of edge variables and low-frequency but high-value terms suggests that while average trends are well-characterized, individual variability is not deeply addressed. Most studies employ uniform protocols, yet it is well documented that individuals respond differently to the same training or nutrition regimen [82–84]. Recently, the concept of "non-responders" to training has been debated, with suggestions that so-called non-responders may simply need a different stimulus or higher dose to elicit gains [85, 86]. Few studies have systematically varied training or diet on an individual basis in real time (adaptive interventions).

Future research should focus on identifying predictors of individual variability in training and nutritional responsiveness, such as genotype, muscle fiber type, and gut microbiota composition, in order to develop personalized intervention strategies [87] Specific gene polymorphisms may modulate individual adaptations to key parameters, including leucine-rich diets, training load, or frequency. Nutrigenomic studies are increasingly elucidating the regulatory roles of genes in protein metabolism, muscle protein synthesis, and exercise adaptation [88]. Recent large-scale population studies have demonstrated significant associations between genetic variations in key enzymes of the serine biosynthesis pathway—such as PHGDH, PSPH, and SHMT1—and appendicular lean mass. These findings suggest that the genetic architecture of specific metabolic pathways may influence hypertrophic potential [89]. In addition, Edman et al. [90] provided comprehensive evidence from both human training interventions and murine models that the MYC gene plays a central role in skeletal muscle hypertrophy. By regulating ribosome biogenesis and translational activity, MYC markedly enhances muscle cross-sectional area and mass. Incorporating such genetic information into hypertrophy-focused intervention design may enable precise modulation of protein source selection, supplementation strategies, and training volume. Chambers and Murach [89] further emphasized that the rapid advancement of high-throughput technologies—including transcriptomics, epigenomics, proteomics, phosphoproteomics, and single-cell omics—has led to key breakthroughs in understanding load-induced muscle adaptation. The integration of multi-omics data through artificial intelligence and machine learning approaches holds transformative potential for uncovering interindividual differences in hypertrophic responses and developing truly personalized nutrition-training interventions.

Discussion

Synthesis of key findings and trends

This scientometric analysis provides a comprehensive synthesis of three decades of research at the intersection of nutritional interventions and resistance training for muscle hypertrophy. The findings reveal distinct developmental trends and dominant themes, while also identifying specific gaps that warrant further investigation. Below, we interpret these results in the context of our research objectives and the existing literature, highlighting how our analysis aligns with or diverges from established knowledge in exercise and nutrition science.

Dominant nutritional strategies and training combinations Our analysis shows that protein supplementation (often with amino acids or whey protein) paired with resistance training is by far the most studied strategy, reflecting a consensus that adequate protein is critical for maximizing training-induced muscle gains [92]. This finding aligns with numerous meta-analyses and position stands. For example, Morton et al. (2018) demonstrated that dietary protein supplementation significantly enhances gains in muscle mass and strength during prolonged resistance training [93]. Similarly, the International Society of Sports Nutrition (ISSN) position stand on protein and exercise recommends 1.4–2.0 g/kg/day protein for most exercising individuals, noting that protein ingestion synergistically improves resistance training outcomes [94].

Creatine supplementation is another prominent strategy identified in our co-occurrence analysis (e.g., "creatine × strength training"), consistent with its well-documented efficacy for increasing high-intensity exercise capacity and muscle mass over time [95–97]. The ISSN's position stand on creatine confirms it as the most effective ergogenic supplement for lean mass and strength gains in conjunction with training [98, 99].

Other nutritional compounds (e.g. specific amino acids like leucine, β-hydroxy-β-methylbutyrate (HMB), or omega-3 fatty acids) appear less frequently in the literature; when they do appear, it is often alongside protein or as refinements to protein-centric strategies. For instance, leucine is frequently studied as the key amino acid driving muscle protein synthesis [9, 100, 101]. Our results indicate that while such additional supplements have been investigated, none has displaced protein or creatine as a core strategy—likely because their effects are smaller or more context-dependent. For example, branched-chain amino acids alone do not maximally stimulate muscle protein synthesis without sufficient dietary protein, and HMB's benefits are primarily observed in untrained or elderly populations [102, 103].

Stable research combinations and evolving themes We identified that certain combinations of variables recur frequently, indicating stable research models. For instance, the clustering of "resistance training – protein – muscle hypertrophy" variables and similar triads suggests that many studies use a common template: a resistance exercise program, a nutritional intervention (often protein supplementation), and outcome measures of muscle size or synthesis rates. This convergence has advantages: it allows for meta-analyses and cross-comparison (since studies have compatible designs) and has led to robust conclusions (e.g., protein supplementation benefits, as noted above). Over time, the field has expanded these models to new contexts, which is evident in the thematic evolution.

In earlier years, the focus within these combinations was mechanistic (e.g., measuring muscle protein synthesis or signaling molecules like mTOR). In later years, as our burst analysis shows, the focus shifted to applied outcomes (e.g., training performance, sarcopenia prevention). This evolution mirrors the broader trend of translating mechanistic insight into practical applications. For example, early research established that whey protein is rapidly digested and rich in leucine, leading to greater acute MPS [104, 105]. Subsequent studies then tested whey protein supplementation in training interventions, and eventually in older adults with sarcopenia, demonstrating real-world benefits (e.g., improved muscle mass and function) [106–108]. Thus, what started as a mechanistic finding became an applied strategy—a trajectory clearly reflected in our analysis (from red cluster keywords to blue cluster keywords over time). The presence of a distinct blue cluster focusing on aging and recovery suggests that one stable combination now is resistance exercise plus nutritional support specifically for older populations.

Indeed, recent systematic reviews confirm that protein supplementation combined with resistance training can modestly but significantly enhance lean mass and strength gains in older adults [109]. Some studies have found no added benefit of extra protein beyond an adequate diet in the elderly [110], but on balance the evidence supports protein-plus-training as beneficial in this group. This underscores a point implied by our findings: established interventions may need to be contextualized for specific populations. What works in young, athletic populations (e.g. high protein intake coupled with high-volume training) might require adaptation for older individuals—for example, more emphasis on protein timing around exercise to overcome anabolic resistance, or adding nutrients like omega-3 fatty acids to enhance muscle protein sensitivity [111, 112]. The literature has begun to reflect these nuances, but our analysis suggests there is room for more targeted research in under-studied subpopulations (such as women, older adults, and clinical groups), using the proven base interventions as a starting point and refining them for each group's physiological context.

Shift from mechanistic to applied focus The trend in keyword bursts and topic evolution clearly indicates that contemporary research has become more application-focused compared to the 1990s and early 2000s. Early pioneering studies answered fundamental questions about muscle biology—for instance, how resistance exercise activates mTOR signaling or how amino acid ingestion post-exercise stimulates muscle protein synthesis [113, 114]. These studies were crucial in establishing the rationale for nutritional interventions. However, as the field matured, the emphasis shifted to leveraging this knowledge in practice. Our results align with this trajectory: recent high-frequency terms like "older adults," "training," and "dietary protein" reflect studies concerned with outcomes in specific populations and real-world program optimization, rather than isolated biochemical events. This shift is also apparent in the collaborations and journals: clinical and multidisciplinary journals (e.g., Nutrients, Frontiers in Nutrition) now contribute a large share of publications, whereas earlier much of the work might appear in basic science journals. The discussion in the field now often revolves around how to implement findings—for instance, how much protein is optimal per meal, or how to combine resistance training with aerobic exercise without impairing hypertrophy [115, 116]–questions aimed at practical guidance.

It's important to note that this applied shift does not diminish the value of mechanistic research; rather, it builds upon it. Indeed, some contemporary studies still integrate both, such as measuring molecular responses within an applied trial to understand individual differences [117]. This integrative approach is recommended to continue. Nonetheless, the net effect of the shift is a field that increasingly produces findings directly relevant to athletes, coaches, and clinicians. For example, our analysis highlights the rise in research targeting sarcopenia. A decade or two ago, "sarcopenia" and "older adults" were not common terms in muscle hypertrophy research—now they are central [118]. This reflects an appreciation that hypertrophy is not just for bodybuilders but is critically important for healthy aging and rehabilitation. Leading journals have published consensus statements advocating resistance training and adequate protein as frontline interventions against age-related muscle loss [119–121], and our findings show the research community has answered this call. Consequently, the scope of "muscle hypertrophy" research has broadened to include outcomes like improved functional capacity, reduced fall risk, or metabolic improvements in older populations—outcomes that weren't on the radar of early mechanistic studies. This broadening is a positive development, anchoring the field in a wider societal relevance.

Implications for future research

The research gaps identified in Sect. "Research gaps and future directions" point to several strategic directions moving forward, which are echoed by other experts and emerging studies.

Firstly, increasing the inclusion of female participants in hypertrophy studies is essential**.** Not only are there physiological differences to explore (such as the potential influence of menstrual cycles or oral contraceptives on training adaptations), but as James et al. highlighted, the underrepresentation of women can lead to findings that may not fully generalize [122]. Encouragingly, recent meta-analyses report that, when women are studied, their hypertrophic responses to training are on par with men's when volume and intensity are equated [63]. This suggests that many principles (e.g., progressive overload, protein intake) are broadly applicable, but it remains important to confirm and refine guidelines specifically for women (considering factors like lower baseline muscle mass, or nutrient considerations such as iron status). Some ongoing studies are now examining if follicular versus luteal phase training yields different results; so far, evidence is mixed with no large effects observed [123], pointing toward similar training recommendations year-round, with perhaps individual adjustments. Our findings underscore that such nuance is largely absent from past literature—a gap future research is beginning to fill.

Secondly, personalization will likely be a major theme. The concept of non-responders to uniform programs implies a need for adaptive approaches [83]. Advances in genomics and molecular profiling (for example, identifying polymorphisms that affect muscle growth or nutrient metabolism) present opportunities to tailor interventions. Guest et al. have shown that genetic differences (e.g., in caffeine metabolism or vitamin D receptors) can impact individual responses in sports performance [87]; applying similar nutrigenomic insights to hypertrophy (such as genes related to muscle protein turnover or anabolic signaling) could allow practitioners to predict who might need a higher protein intake or who might benefit from certain supplements. While the science of precision exercise nutrition is still developing, our analysis suggests that the era of one-size-fits-all recommendations is giving way to more nuanced protocols. This is supported by the high variability often seen in study results (large standard deviations for gains, etc.), which researchers are now exploring via subgroup analyses or cluster analyses. For example, a recent cluster analysis by Villanueva et al. in older adults found distinct responder groups to protein and exercise interventions, indicating that factors like habitual activity level could influence who benefits most. Embracing such heterogeneity in future study designs (rather than averaging it out) will be important [124].

Thirdly, the field is likely to integrate recovery and injury prevention outcomes more explicitly. Given that muscle hypertrophy programs can be taxing, research may expand to consider how nutritional interventions can mitigate training fatigue or overtraining. We saw "recovery" emerging in the literature; building on that, future work might address questions such as optimal protein and carbohydrate mix for back-to-back training days, or nutritional support (like collagen or vitamin C) for connective tissue to handle heavier loads as muscles grow. This intersects with rehabilitation: larger muscle mass and strength can protect against injury, but heavy training can also predispose to strains if not managed [125, 126]. Nutrition (adequate protein, anti-inflammatories, etc.) plays a preventive role here and warrants further study.

Lastly, integrating multiple modalities (e.g., endurance exercise for cardiovascular health) without compromising hypertrophy is an area of active inquiry (often referred to as the concurrent training puzzle). Our results show this is part of the broader conversation (as "physical activity" appears in clusters with lower frequency), and future guidelines will likely emphasize comprehensive fitness programs. Recent work suggests that when volume and intensity are properly managed, concurrent training can yield gains in both domains [127, 128]. Nutritional strategies (like ensuring sufficient protein and total calories) are key to supporting this, and research bridging traditionally separate domains (endurance and strength nutrition) will be beneficial.

Limitations and methodological considerations

Despite offering a systematic framework for mapping knowledge structures and research evolution, our scientometric approach has inherent limitations. First, the analysis relied solely on the Web of Science Core Collection database which, while authoritative, may underrepresent regional journals or non-English publications. This introduces a potential language and geographic bias in the dataset. Second, we included only peer-reviewed journal articles, excluding gray literature such as conference proceedings, policy papers, and technical reports. As a result, certain practical insights or emerging findings disseminated outside of indexed journals might have been overlooked. Third, our reliance on citation-based metrics and keyword co-occurrence frequencies can create a temporal lag in detecting emerging trends, potentially underestimating the impact of very recent high-quality studies that have not yet accumulated citations.

To address these issues, future scientometric research in this area should consider several enhancements. Integrating multiple literature databases (e.g., Scopus or Dimensions) would capture a broader range of publications and reduce database-specific bias. Including gray literature and subject matter expert input in the analysis could also surface practice-oriented contributions that formal journal articles might miss. Moreover, adopting mixed-method approaches—combining quantitative mapping with qualitative content analysis—could enrich our understanding of thematic evolution and improve the practical relevance of the conclusions. For instance, as Azizan et al. suggest [129], coupling traditional scientometric mapping with in-depth content analysis of article full-texts or expert surveys may yield deeper insights into emerging research fronts and help validate that the identified themes truly correspond to impactful real-world strategies.

Practical implications and recommendations

The knowledge map developed in this study for the domain of nutritional interventions–resistance training–muscle hypertrophy carries significant practical implications across multiple levels, including research planning, higher education, scientific collaboration, and policy development. The revealed structural patterns and thematic evolution trends offer an evidence-based foundation to inform strategic decision-making in related fields such as exercise science, sports nutrition, and health promotion.

In terms of research funding, the critical gaps identified—such as the underrepresentation of women and older adults, as well as the lag in studies on nutritional periodization and recovery mechanisms—can help guide resource allocation and agenda setting. Funding agencies may prioritize inclusive and translational research initiatives that are better positioned to address real-world health challenges.

In the context of higher education, these findings can support the optimization of curricula related to sports nutrition, resistance training, and functional rehabilitation. By integrating the latest scientific evidence into academic programs, universities and professional training institutions can better align with industry needs and cultivate a workforce equipped with both practical competencies and research literacy.

For researchers, the author-, institution-, and collaboration-network maps generated in this analysis offer empirical support for forming strategic partnerships, refining research foci, and improving research efficiency. By identifying leading themes and emerging clusters, this study enables scholars to target high-impact areas and avoid redundant efforts.

Moreover, the study provides actionable insights to support evidence-based policymaking. Public health organizations and guideline development bodies may draw upon these findings to formulate personalized recommendations for specific populations—such as women, older adults, or clinical groups affected by sarcopenia. Overall, by integrating multiple scientometric tools and analytical techniques, this study not only enhances our understanding of how the field has evolved but also delivers a multidimensional knowledge base to inform research practice and health promotion strategies.

Conclusion

Future research directions

Building on the findings of this study, several concrete questions merit attention in future research. One key question is how training and nutritional protocols can be better tailored to female physiology and to older populations in order to maximize muscle hypertrophy outcomes in those groups. Another open question is which specific nutritional strategies most effectively support recovery processes and metabolic health when combined with resistance training programs. It also remains to be determined how periodized nutrition plans might be optimally synchronized with periodized training cycles to enhance long-term hypertrophy and performance. Finally, an important frontier is how emerging technologies in genomics, metabolomics, and other "omics" can be harnessed to design truly personalized training and nutrition interventions. Addressing these questions through well-designed studies will help fill the gaps identified by our scientometric analysis and drive the field forward.

Key conclusions

In summary, this scientometric analysis systematically mapped the evolution, thematic structure, and research trends of the nutritional intervention and resistance training field from 1992 to 2025. A clear picture emerged of a core intervention paradigm centered on protein supplementation combined with resistance exercise, which has consistently been the predominant strategy for promoting muscle hypertrophy. This core strategy is supported by a broad consensus in the literature regarding its synergistic effect on muscle growth, and is reflected in the stable presence of studies focused on "protein + training" interventions across decades. At the same time, our analysis revealed that the field has undergone a notable shift in focus over the years: what began as primarily mechanistic research (e.g., molecular signaling pathways of muscle growth) has progressively transitioned toward applied research targeting practical outcomes such as improvements in muscle strength, physical performance, and the management of sarcopenia. Thematically, the literature shows considerable structural stability (with recurring combinations of topics and methods), but also adaptive expansion into new areas (for instance, applying the protein-and-training paradigm to older adults, or integrating concepts of recovery and personalized nutrition). Taken together, these conclusions illustrate a field that has solidified its foundational strategies and is now branching out to address more diverse and applied questions.

Implications for practice and policy

From a practical standpoint, our findings reinforce several important points for exercise professionals and policy-makers. Most fundamentally, they underscore the effectiveness of combining targeted nutrition with resistance training for enhancing muscle mass and function. For example, ensuring adequate protein intake (and using evidence-backed supplements like creatine when appropriate) alongside structured resistance exercise should remain a cornerstone of training guidelines for athletes, older adults, and other populations aiming to improve muscle health.

In addition, the highlighted research gaps carry practical significance: the need to include women and non-Western populations in research suggests that training and dietary guidelines should be adapted to be more inclusive and individualized. The underexplored areas of recovery nutrition and nutritional periodization indicate that coaches and clinicians could improve outcomes by incorporating strategies such as optimized between-session nutrition and diet plans that vary with training cycles.

Finally, the emergence of precision nutrition and training points toward a future where practitioners will use genetic or phenotypic information to tailor programs to each individual. In essence, this study provides a scientific basis for refining existing best practices and developing new, evidence-based policies—whether in athletic training programs, clinical rehabilitation, or public health initiatives—to more effectively promote muscle hypertrophy and overall muscle health across diverse populations.

Appendix A: Expert Validation of Search Strategy

To ensure the methodological rigor and thematic coverage of the Scientometric search strategy, two independent experts in the field ofexercise and nutrition were consulted during the initial development of the Boolean search formulation used in this study. Through prioracademic discussions and professional communication, both experts confirmed that the search logic was sound and that the selected termsadequately captured the core concepts of the research domain. The written confirmation presented here serves as formal documentation oftheir prior validation. Their names, academic affiliations, and professional titles are listed below:

Dr. Juanjuan Hu

Associate Professor/Director, Teaching and Research Division of Competitive Training and Scientific Research; Chengdu College of University of Electronic Science And Technology of China, China

Dr. Kun Wang

Professor, School of Kinesiology and Health Sciences; Xi'an Physical Education University, China.

Abbreviations

AB	Abstract
AK	Author keywords
TI	Title
Freq (%)	Frequency (percentage)
h_index	Hirsch Index
HMB	β-Hydroxy-β-methylbutyrate
KP	Keywords plus
MAPK	Mitogen-activated protein kinase
mTOR	Mechanistic target of rapamycin
MPS	Muscle protein synthesis
MTCP	Mean total citations per year
PRISMA	Preferred reporting items for systematic reviews and meta-analyses
PY_start	Publication year start
RCT	Randomized controlled trial
SCI	Science Citation Index
SCIE/SSCI	Science Citation Index Expanded/Social Sciences Citation Index
Scientometric	Scientometric analysis
TC	Total citations
TLS	Total link strength
TS	Topic search
WoS CC	Web of science core collection

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s41043-025-01031-w.

Additional file 1 (DOCX 27 KB)

Acknowledgements

The author extends heartfelt appreciation for the academic training and long-term mentorship received during the doctoral journey, which laid a solid foundation for conducting this independent research. Sincere thanks are also owed to the two domain experts whose methodological advice during the early development of the search strategy significantly contributed to the study's rigor. Deep appreciation is further extended to the journal's editor and anonymous reviewers for their thoughtful critiques and constructive suggestions, which have greatly enhanced the clarity, coherence, and scientific quality of the manuscript.

Author contributions

Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization, project administration: Chen Wei. The author confirms sole responsibility for all aspects of the work. (The author is currently a PhD candidate in Sports Science at Universiti Teknologi Malaysia.)

Funding

This research received no external funding.

Data availability

All results are available in the text of the manuscript, figures and Tables. The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation. The authors can be contacted by e-mail upon request. Correspondence: wei-1991@graduate.utm.my.

Declarations

Ethics approval and consent to participate

This study did not involve human participants or animal subjects. All data were retrieved from the publicly accessible Web of Science Core Collection; consequently, formal ethical approval and informed-consent procedures were not required.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Author details

[1]Physical Education Department, Shaanxi Railway Institute, Weinan 714000, People's Republic of China. [2]Faculty of Educational Sciences and Technology, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.

Received: 3 May 2025 Accepted: 25 July 2025
Published online: 01 August 2025

References

1. Wolfe RR. The underappreciated role of muscle in health and disease. Am J Clin Nutr. 2006;84(3):475–82.
2. Karagounis LG, Hawley JA. Skeletal muscle: increasing the size of the locomotor cell. Int J Biochem Cell Biol. 2010;42(9):1376–9.
3. Biłogras J, Kostelecka K, Byliński Ł, Wais M, Gruca D, Warchoł K. Muscle hypertrophy in athlete training from a medical point of view - what do we know. J Educ Health Sport. 2023;50(1):92–106.
4. Rolnick N, Schoenfeld BJ. Blood flow restriction training and the physique athlete: a practical research-based guide to maximizing muscle size. Strength Cond J. 2020;42(5):22.
5. Guimaraes-Ferreira L, Cholewa JM, Naimo MA, Zhi XIA, Magagnin D, Dal Ponte de Sa RB, et al. Synergistic effects of resistance training and protein intake: practical aspects. Nutrition. 2014;30(10):1097–103.
6. Bamman MM, Roberts BM, Adams GR. Molecular regulation of exercise-induced muscle fiber hypertrophy. Cold Spring Harb Perspect Med. 2018;8(6): a029751.
7. Abdollahi H, Salehinia F, Badeli M, Karimi E, Gandomkar H, Asadollahi A, et al. The biochemical parameters and Vitamin D levels in ICU patients

with Covid-19: a cross-sectional study. Endocr Metab Immune Disord Drug Targets. 2021;21(12):2191–202.
8. Karimi E, Gholizadeh M, Abdolahi M, Sedighiyan M, Salehinia F, Siri G, et al. Effect of vitamin B1 supplementation on blood creatinine and lactate levels and clinical outcomes in patients in intensive care units: a systematic review and meta-analysis of randomized controlled trials. Nutr Rev. 2024;82(6):804–14.
9. Ely IA, Phillips B, Smith K, Wilkinson D, Piasecki M, Breen L, et al. A focus on leucine in the nutritional regulation of human skeletal muscle metabolism in ageing, exercise and unloading states. Clin Nutr. 2023;42(10):1849–65.
10. Kaspy MS, Hannaian SJ, Bell ZW, Churchward-Venne T. The effects of branched-chain amino acids on muscle protein synthesis, muscle protein breakdown, and associated molecular signalling responses in humans: an update. Nutr Res Rev. 2023;1–36.
11. Vossel KV, Hardeel J, Stede TV der, Cools T, Vandecauter J, Vanhaecke L, et al. Evidence for simultaneous muscle atrophy and hypertrophy in response to resistance training in humans. Med Sci Sports Exerc [Internet]. 2024 [cited 2025 Jun 1]; Available from: https://consensus.app/papers/evidence-for-simultaneous-muscle-atrophy-and-hypertrophy-vossel-hardeel/9b5ca4b676a75b64887dc67895b0c3f1/
12. Paoli A, Cerullo G, Bianco A, Neri M, Gennaro F, Charrier D, et al. Not only protein: dietary supplements to optimize the skeletal muscle growth response to resistance training: the current state of knowledge. J Hum Kinet. 2024;91(Spec Issue):225–44.
13. Zeng Y, He X, Peng X, Zhao L, Yin C, Mao S. Combined nutrition with exercise: fueling the fight against sarcopenia through a bibliometric analysis and review. Int J Gen Med. 2024;3(17):1861–76.
14. Monteyne AJ, West S, Stephens FB, Wall BT. Reconsidering the pre-eminence of dietary leucine and plasma leucinemia for predicting the stimulation of postprandial muscle protein synthesis rates. Am J Clin Nutr. 2024;120:7–16.
15. Thomas ACQ, Stead CA, Burniston JG, Phillips SM. Exercise-specific adaptations in human skeletal muscle: molecular mechanisms of making muscles fit and mighty. Free Radic Biol Med. 2024;1(223):341–56.
16. Bagheri R, Karimi Z, Camera DM, Scott D, Bashirzad MZ, Sadeghi R, et al. Association between changes in lean mass, muscle strength, endurance, and power following resistance or concurrent training with differing high protein diets in resistance-trained young males. Front Nutr [Internet]. 2024 Aug 14 [cited 2025 Jun 1];11. Available from: https://doi.org/10.3389/fnut.2024.1439037/full
17. Deane CS, Cox J, Atherton PJ. Critical variables regulating age-related anabolic responses to protein nutrition in skeletal muscle. Front Nutr [Internet]. 2024 Aug 6 [cited 2025 Jun 1];11. Available from: https://doi.org/10.3389/fnut.2024.1419229/full
18. Chen W, Morazuki SR. Bibliometric analysis on bodybuilding. J Infrastruct Policy Dev. 2024;8(11):9018.
19. Wei C, Morazuki SR. The effects of resistance training on overweight: a bibliometric analysis. RBNE-Rev Bras Nutr ESPORTIVA. 2024;18(113):596–615.
20. Aria M, Cuccurullo C. *bibliometrix*: an R-tool for comprehensive science mapping analysis. J Informetr. 2017;11(4):959–75.
21. Shen X, Wang L. Topic evolution and emerging topic analysis based on open source software. J Data Inf Sci. 2020;5(4):126–36.
22. Chen C. CiteSpace: a practical guide for mapping scientific literature [Internet]. Nova Science Publishers Hauppauge, NY, USA; 2016 [cited 2025 Apr 7]. Available from: http://www.dobraca.com/wp-content/uploads/2019/03/CiteSpacePracticalGuide-Nova-Sample1-50pp.pdf
23. Azizan A. Exercise and frailty in later life: a systematic review and bibliometric analysis of research themes and scientific collaborations. Int J Popul Stud. 2024;11(1):1–15.
24. Birkle C, Pendlebury DA, Schnell J, Adams J. Web of Science as a data source for research on scientific and scholarly activity. Quant Sci Stud. 2020;1(1):363–76.
25. Kai L, Rollins J, Yan E. Web of Science use in published research and review papers 1997–2017: a selective, dynamic, cross-domain, content-based analysis. Scientometrics. 2018;115(1):1–20.
26. Azizan A. Challenges and opportunities in sensor-based fall prevention for older adults: a bibliometric review. J Enabling Technol. 2024;18(4):306–18.
27. Azizan A, Cao S, Dahlan A, Endrini S. Mapping knowledge landscapes and emerging trends in digital biomarkers for dementia in older adults: a scoping and bibliometric analysis. Arch Gerontol Geriatr Plus. 2025;2(2): 100148.
28. Rasmussen BB, Phillips SM. Contractile and nutritional regulation of human muscle growth. Exerc Sport Sci Rev. 2003;31(3):127.
29. Phillips SM. Protein requirements and supplementation in strength sports. Nutrition. 2004;20(7):689–95.
30. Phillips SM, Van Loon LJC. Dietary protein for athletes: from requirements to optimum adaptation. J Sports Sci. 2011;29(sup1):S29-38.
31. Phillips SM. A brief review of critical processes in exercise-induced muscular hypertrophy. SPORTS Med. 2014;44:71–7.
32. Phillips SM, Martinson W. Nutrient-rich, high-quality, protein-containing dairy foods in combination with exercise in aging persons to mitigate sarcopenia. Nutr Rev. 2019;77(4):216–29.
33. Phillips SM. The science of muscle hypertrophy: making dietary protein count. Proc Nutr Soc. 2011;70(1):100–3.
34. Tipton KD, Elliott TA, Cree MG, Wolf SE, Sanford AP, Wolfe RR. Ingestion of casein and whey proteins result in muscle anabolism after resistance exercise. Med Sci Sports Exerc. 2004;36(12):2073.
35. Azizan A, Endrini S, Abdullah KH. A research landscape analysis on Alzheimer's disease and gerontechnology: Identifying key contributors, hotspots, and emerging trends. Arch Gerontol Geriatr Plus. 2025;2(1): 100125.
36. Podrigalo L, Tymchenko K, Perevoznyk V, Semeniv B, Paievskyi V, Halashko O. Scientific support for strength sports: analysis of scientific resources from the Web of Science Core Collection. Pedagogy Phys Cult Sports. 2025;29(1):44–61.
37. Xu F, Zeng J, Liu X, Lai J, Xu J. Exercise-induced muscle damage and protein intake: a bibliometric and visual analysis. Nutrients. 2022;14(20):4288.
38. Fujita MSL. Análise das funções de palavras-chave atribuídas por autores em publicações científicas de eventos e periódicos. RDBCI Rev Digit Bibl E Ciênc Informação. 2024;4(22): e024020.
39. Kagan SH. Anchoring our science with keywords. Int J Older People Nurs. 2024;19(2): e12607.
40. Zhang J, Yu Q, Zheng F, Long C, Lu Z, Duan Z. Comparing keywords plus of WOS and author keywords: a case study of patient adherence research. J Assoc Inf Sci Technol. 2016;67(4):967–72.
41. Lu W, Liu Z, Huang Y, Bu Y, Li X, Cheng Q. How do authors select keywords? A preliminary study of author keyword selection behavior. J Informetr. 2020;14(4): 101066.
42. Smith GD. Getting the most out from keywords. J Clin Nurs. 2021;30(7–8):e23–4.
43. Yarasheski KE, Campbell JA, Smith K, Rennie MJ, Holloszy JO, Bier DM. Effect of growth hormone and resistance exercise on muscle growth in young men. Am J Physiol-Endocrinol Metab. 1992;262(3):E261–7.
44. Wang N, Hikida RS, Staron RS, Simoneau JA. Muscle fiber types of women after resistance training—Quantitative ultrastructure and enzyme activity. Pflüg Arch. 1993;424(5):494–502.
45. Campbell WW, Crim MC, Young VR, Joseph LJ, Evans WJ. Effects of resistance training and dietary protein intake on protein metabolism in older adults. Am J Physiol-Endocrinol Metab. 1995;268(6):E1143–53.
46. Slater GJ, Jenkins D. β-Hydroxy-β-Methylbutyrate (HMB) Supplementation and the Promotion of Muscle Growth and Strength. Sports Med. 2000;30(2):105–16.
47. Bamman MM, Shipp JR, Jiang J, Gower BA, Hunter GR, Goodman A, et al. Mechanical load increases muscle IGF-I and androgen receptor mRNA concentrations in humans. Am J Physiol-Endocrinol Metab. 2001;280(3):E383–90.
48. Deldicque L, Theisen D, Francaux M. Regulation of mTOR by amino acids and resistance exercise in skeletal muscle. Eur J Appl Physiol. 2005;94(1):1–10.
49. Kraemer WJ, Ratamess NA. Hormonal responses and adaptations to resistance exercise and training. Sports Med. 2005;35(4):339–61.
50. Hulmi JJ, Lockwood CM, Stout JR. Effect of protein/essential amino acids and resistance training on skeletal muscle hypertrophy: a case for whey protein. Nutr Metab. 2010;7(1):51.
51. Moore DR, Atherton PJ, Rennie MJ, Tarnopolsky MA, Phillips SM. Resistance exercise enhances mTOR and MAPK signalling in human

muscle over that seen at rest after bolus protein ingestion. Acta Physiol. 2011;201(3):365–72.
52. Joy JM, Lowery RP, Wilson JM, Purpura M, De Souza EO, Wilson SM, et al. The effects of 8 weeks of whey or rice protein supplementation on body composition and exercise performance. Nutr J. 2013;12(1):86.
53. Damas F, Phillips S, Vechin FC, Ugrinowitsch C. A review of resistance training-induced changes in skeletal muscle protein synthesis and their contribution to hypertrophy. Sports Med. 2015;45(6):801–7.
54. Stokes T, Hector AJ, Morton RW, McGlory C, Phillips SM. Recent perspectives regarding the role of dietary protein for the promotion of muscle hypertrophy with resistance exercise training. Nutrients. 2018;10(2):180.
55. Moore DR. Maximizing Post-exercise Anabolism: The Case for Relative Protein Intakes. Front Nutr [Internet]. 2019 Sep 10 [cited 2025 May 31];6. Available from: https://doi.org/10.3389/fnut.2019.00147/full
56. Endo Y, Nourmahnad A, Sinha I. Optimizing Skeletal Muscle Anabolic Response to Resistance Training in Aging. Front Physiol [Internet]. 2020 Jul 23 [cited 2025 May 31];11. Available from: https://doi.org/10.3389/fphys.2020.00874/full
57. Roschel H, Hayashi AP, Fernandes AL, Jambassi-Filho JC, Hevia-Larraín V, de Capitani M, et al. Supplement-based nutritional strategies to tackle frailty: A multifactorial, double-blind, randomized placebo-controlled trial. Clin Nutr. 2021;40(8):4849–58.
58. Kirwan RP, Mazidi M, Rodríguez García C, Lane KE, Jafari A, Butler T, et al. Protein interventions augment the effect of resistance exercise on appendicular lean mass and handgrip strength in older adults: a systematic review and meta-analysis of randomized controlled trials. Am J Clin Nutr. 2022;115(3):897–913.
59. Bagheri R, Shakibaee A, Camera DM, Sobhani V, Ghobadi H, Nazar E, et al. Effects of 8 weeks of resistance training in combination with a high protein diet on body composition, muscular performance, and markers of liver and kidney function in untrained older ex-military men. Front Nutr [Internet]. 2023 Jun 29 [cited 2025 May 31];10. Available from: https://doi.org/10.3389/fnut.2023.1205310/full
60. Tang C, Xi T, Zheng J, Cui X. Chemical properties of whey protein in protein powders and its impact on muscle growth in athletes: a review. Nat Prod Commun. 2025;20(3):1934578X251326124.
61. Rathmacher JA, Pitchford, Lisa M, Stout, Jeffrey R, Townsend, Jeremy R, Jäger, Ralf, Kreider, Richard B, et al. International society of sports nutrition position stand: β-hydroxy-β-methylbutyrate (HMB). J Int Soc Sports Nutr. 2025;22(1):2434734.
62. Anderson N, Robinson DG, Verhagen E, Fagher K, Edouard P, Rojas-Valverde D, et al. Under-representation of women is alive and well in sport and exercise medicine: what it looks like and what we can do about it. BMJ Open Sport Exerc Med. 2023;9(2):e001606.
63. Roberts BM, Nuckols G, Krieger JW. Sex differences in resistance training: a systematic review and meta-analysis. J Strength Cond Res. 2020;34(5):1448–60.
64. McNulty KL, Elliott-Sale KJ, Dolan E, Swinton PA, Ansdell P, Goodall S, et al. The effects of menstrual cycle phase on exercise performance in eumenorrheic women: a systematic review and meta-analysis. Sports Med Auckl NZ. 2020;50(10):1813–27.
65. Colenso-Semple LM, D'Souza AC, Elliott-Sale KJ, Phillips SM. Current evidence shows no influence of women's menstrual cycle phase on acute strength performance or adaptations to resistance exercise training. Front Sports Act Living. 2023;5:1054542.
66. Sakamaki-Sunaga M, Min S, Kamemoto K, Okamoto T. Effects of menstrual phase–dependent resistance training frequency on muscular hypertrophy and strength. J Strength Cond Res [Internet]. 2016 [cited 2025 Apr 7];30. Available from: https://consensus.app/papers/effects-of-menstrual-phase%E2%80%93dependent-resistance-sakamaki-sunaga-min/696e2c917afe5bf1aa5dd87e9c421b17/
67. Ose BM, Eisenhauer J, Roepe IG, Herda A, Vopat BG, Vopat L. Where are all the female participants in sports and exercise medicine research? A decade later. Am J Sports Med [Internet]. 2025 [cited 2025 Apr 7]; Available from: https://consensus.app/papers/where-are-all-the-female-participants-in-sports-and-ose-eisenhauer/69c74ca1c910514b9177fc93fe5b9e92/
68. O'Connor E, Mündel T, Barnes MJ. Nutritional compounds to improve post-exercise recovery. Nutrients. 2022;14(23):5069.
69. Paquin J, Tremblay R, Islam H, Riesco E, Marcotte-Chénard A, Dionne IJ. Resistance training, skeletal muscle hypertrophy, and glucose homeostasis: how related are they? A systematic review and meta-analysis. Appl Physiol Nutr Metab. 2024;49(12):1622–35.
70. Acosta-Manzano P, Rodriguez-Ayllon M, Acosta F, Niederseer D, Niebauer J. Beyond general resistance training. Hypertrophy versus muscular endurance training as therapeutic interventions in adults with type 2 diabetes mellitus: A systematic review and meta-analysis. Obes Rev [Internet]. 2020 [cited 2025 Apr 7];21. Available from: https://consensus.app/papers/beyond-general-resistance-training-hypertrophy-versus-acosta%E2%80%90manzano-rodriguez-ayllon/27a4c865745b58f4966cc59bc127820f/
71. Mota JA, Nuckols G, Smith-Ryan AE. Nutritional periodization: applications for the strength athlete. Strength Cond J. 2019;41(5):69.
72. Wikström-Frisén L, Boraxbekk C, Henriksson-Larsén K. Effects on power, strength and lean body mass of menstrual/oral contraceptive cycle based resistance training. J Sports Med Phys Fitness. 2017;57(1–2):43–52.
73. Oxfeldt M, Dalgaard LB, Jørgensen EB, Johansen F, Dalgaard EB, Ørtenblad N, et al. Molecular markers of skeletal muscle hypertrophy following 10 weeks of resistance training in oral contraceptive users and non-users. J Appl Physiol [Internet]. 2020 [cited 2025 Apr 7]; Available from: https://consensus.app/papers/molecular-markers-of-skeletal-muscle-hypertrophy-oxfeldt-dalgaard/0781abbed6ce5c9aac9ede9312073484/
74. Di Gioia G, Vespasiano F, Celeski M, Luvero D, Crispino SP, Mango F, et al. From menstrual cycle to pregnancy and motherhood: the tough path to be a female athlete. Sport Sci Health. 2025;11:1–14.
75. Jacobs J, Brandt, Corlia, Grobler, Nico, Saw, Anna, Olivier B. Applied sports science and medicine for female cricket players: systematic scoping review. J Sports Sci. 2025;43(8):803–20.
76. Ayyub S, Agrawal M, Sharma V, Aravind A. The effect of physical activity on premenstrual syndrome: a systematic review. Ann Neurosci. 2024;16:09727531241297012.
77. Ahmadi F, Khaleghi MM, Zar A. The therapeutic effect of different exercises on premenstrual syndrome (PMS): a systematic review. 2025 Jan 7 [cited 2025 May 31]; Available from: https://brill.com/view/journals/cep/21/1/article-p17_2.xml
78. Burley SD, Whittingham-Dowd J, Allen J, Grosset J, Onambélé-Pearson G. The Differential Hormonal Milieu of Morning versus Evening May Have an Impact on Muscle Hypertrophic Potential. PLoS ONE [Internet]. 2016 [cited 2025 Apr 7];11. Available from: https://consensus.app/papers/the-differential-hormonal-milieu-of-morning-versus-burley-whittingham-dowd/4ea4cfa1a1105ca484ca5f14efcc8137/
79. Harmsen JF, Kotte M, Habets I, Bosschee F, Frenken K, Jorgensen JA, et al. Exercise training modifies skeletal muscle clock gene expression but not 24-hour rhythmicity in substrate metabolism of men with insulin resistance. J Physiol. 2023;602:6417–33.
80. Robertson CM, Pullinger S, Robinson WR, Smith ME, Burniston J, Edwards BJ. Circadian variation in muscle force output in males using isokinetic, isometric dynamometry: can we observe this in multi-joint movements using the muscleLab force-velocity encoder and are they similar in peak and magnitude? Chronobiol Int. 2024;41:709–24.
81. Stellingwerff T, Morton J, Burke L. A Framework for Periodized Nutrition for Athletics. Int J Sport Nutr Exerc Metab. 2019;29(2):141–51.
82. Vickers R, Barnard A, Hervig L. A quantitative analysis of the effect of resistance training on strength test score variability. 2009 [cited 2025 Apr 7]; Available from: https://consensus.app/papers/a-quantitative-analysis-of-the-effect-of-resistance-vickers-barnard/958c9d73c39055788db801ebbe814b09/
83. Pickering C, Kiely J. Do non-responders to exercise exist—And if so, what should we do about them? Sports Med Auckl NZ. 2018;49:1–7.
84. Ahtiainen J, Sallinen J, Häkkinen K, Sillanpää E. Inter-individual variation in response to resistance training in cardiometabolic health indicators. Scand J Med Sci Sports. 2020;30:1040–53.
85. Hammarström D, Øfsteng S, Koll L, Hanestadhaugen M, Hollan I, Apró W, et al. Benefits of higher resistance-training volume depends on ribosome biogenesis. bioRxiv [Internet]. 2019 [cited 2025 Apr 7]; Available from: https://consensus.app/papers/benefits-of-higher-resistancetraining-volume-depends-on-hammarstr%C3%B6m-%C3%B8fsteng/d0ca3b4f76c8531faed377c8726b7c87/
86. Nagata C de A, Garcia PA, Hamu TCD da S, Caetano MB, Costa RR, Leal JC, et al. Are dose-response relationships of resistance training reliable

to improve functional performance in frail and pre-frail older adults? A systematic review with meta-analysis and meta-regression of randomized controlled trials. Ageing Res Rev [Internet]. 2023 [cited 2025 Apr 7]; Available from: https://consensus.app/papers/are-doseresponse-relationships-of-resistance-training-nagata-garcia/3ae4f756fdb750208c9fe372163103aa/
87. Guest NS, Horne J, Vanderhout SM, El-Sohemy A. Sport nutrigenomics: personalized nutrition for athletic performance. Front Nutr. 2019;19(6):8.
88. Sorrenti V, Caudullo G, Lucignano F, Fortinguerra S, Zusso M, Giusti P, et al. Personalized sports nutrition: role of nutrients in athletic performance. Sports Exerc Nutr Genomics [Internet]. 2019 [cited 2025 Apr 7]; Available from: https://consensus.app/papers/personalized-sports-nutrition-role-of-nutrients-in-sorrenti-caudullo/c5c0fe3d64b45723b3e3c6a1d10fe316/
89. Baumert P, Mäntyselkä S, Schönfelder M, Heiber M, Jacobs MJ, Swaminathan A, et al. Skeletal muscle hypertrophy rewires glucose metabolism: An experimental investigation and systematic review. J Cachexia Sarcopenia Muscle. 2024;15:989–1002.
90. Edman S, Jones RG III, Jannig PR, Fernandez-Gonzalo R, Norrbom J, Thomas NT, et al. The 24-hour molecular landscape after exercise in humans reveals MYC is sufficient for muscle growth. EMBO Rep. 2024;25(12):5810–37.
91. Chambers TL, Murach KA. A history of omics discoveries reveals the correlates and mechanisms of loading-induced hypertrophy in adult skeletal muscle. 2024 CaMPS young investigator award invited review. Am J Physiol-Cell Physiol. 2025;328(5):C1535–57.
92. Martyna K, Jakub K. Strength Through Science: A Comprehensive Look at Resistance Training and Protein Intake in Muscle Development. Qual Sport [Internet]. 2024 [cited 2025 Apr 7]; Available from: https://consensus.app/papers/strength-through-science-a-comprehensive-look-at-ku%C5%9Bmierska-ku%C5%9Bmierski/5c888246ea315a44b976017e66d46425/
93. Morton RW, Murphy KT, McKellar SR, Schoenfeld BJ, Henselmans M, Helms E, et al. A systematic review, meta-analysis and meta-regression of the effect of protein supplementation on resistance training-induced gains in muscle mass and strength in healthy adults. Br J Sports Med. 2018;52(6):376–84.
94. Campbell B, Kreider RB, Ziegenfuss T, Bounty PL, Roberts M, Burke D, et al. International Society of Sports Nutrition position stand: protein and exercise. J Int Soc Sports Nutr [Internet]. 2007 [cited 2025 Apr 7]; Available from: https://consensus.app/papers/international-society-of-sports-nutrition-position-stand/d69a5b48b8fe5c66a6445011a5d040ad/
95. Cribb PJ, Williams AD, Hayes A. A creatine-protein-carbohydrate supplement enhances responses to resistance training. Med Sci SPORTS Exerc. 2007;39(11):1960–8.
96. Nunes J, Ribeiro A, Schoenfeld B, Tomeleri C, Avelar A, Trindade MCC, et al. Creatine supplementation elicits greater muscle hypertrophy in upper than lower limbs and trunk in resistance-trained men. Nutr Health. 2017;23:223–9.
97. Burke R, Pinero A, Coleman M, Mohan A, Sapuppo M, Augustin F, et al. The effects of creatine supplementation combined with resistance training on regional measures of muscle hypertrophy: a systematic review with meta-analysis. Nutrients. 2023;15(9):2116.
98. Buford T, Kreider R, Stout JR, Greenwood M, Campbell B, Spano M, et al. International Society of Sports Nutrition position stand: creatine supplementation and exercise. J Int Soc Sports Nutr. 2007;4:6–6.
99. Kreider R, Kalman D, Antonio J, Ziegenfuss T, Wildman R, Collins R, et al. International Society of Sports Nutrition position stand: safety and efficacy of creatine supplementation in exercise, sport, and medicine. J Int Soc Sports Nutr [Internet]. 2017 [cited 2025 Apr 7];14. Available from: https://consensus.app/papers/international-society-of-sports-nutrition-position-stand-kreider-kalman/9c21fff30df6581a85ac26fd7f4336c1/
100. Holwerda A, Paulussen K, Overkamp M, Goessens J, Kramer I, Wodzig W, et al. Leucine co-ingestion augments the muscle protein synthetic response to the ingestion of 15 g protein following resistance exercise in older men. Am J Physiol Endocrinol Metab [Internet]. 2019 [cited 2025 Apr 7]; Available from: https://consensus.app/papers/leucine-coingestion-augments-the-muscle-protein-holwerda-paulussen/39d46908407e5b8d8e056fdd78b66c88/
101. Lim C, Traylor DA, McGlory C, Joanisse S, McKendry J, Grewal T, et al. Increased protein intake derived from leucine-enriched protein enhances the integrated myofibrillar protein synthetic response to short-term resistance training in untrained men and women: a 4-day randomized controlled trial. Appl Physiol Nutr Metab Physiol Appl Nutr Metab [Internet]. 2022 [cited 2025 Apr 7]; Available from: https://consensus.app/papers/increased-protein-intake-derived-from-leucineenriched-lim-traylor/b1417c1cc5d05a4eaf323c01c50d7cbd/
102. Lin Z, Zhao A, He J. Effect of β-hydroxy-β-methylbutyrate (HMB) on the Muscle Strength in the Elderly Population: A Meta-Analysis. Front Nutr [Internet]. 2022 [cited 2025 Apr 7];9. Available from: https://consensus.app/papers/effect-of-%CE%B2hydroxy%CE%B2methylbutyrate-hmb-on-the-muscle-lin-zhao/b431ef244b175c5ab039362d62149fa9/
103. Santos CS, Nascimento FEL. Isolated branched-chain amino acid intake and muscle protein synthesis in humans: a biochemical review. Einstein [Internet]. 2019 [cited 2025 Apr 7];17. Available from: https://consensus.app/papers/isolated-branchedchain-amino-acid-intake-and-muscle-santos-nascimento/5c3b0da2517c5fafa699cb4d8f0a96e1/
104. Naclerio F, Seijo M. Whey protein supplementation and muscle mass: current perspectives. Nutr Diet Suppl [Internet]. 2019 [cited 2025 Apr 7]; Available from: https://consensus.app/papers/whey-protein-supplementation-and-muscle-mass-current-naclerio-seijo/414be3586fef5e32a43d359a654597e2/
105. Moro T, Brightwell CR, Velarde B, Fry C, Nakayama K, Sanbongi C, et al. Whey Protein Hydrolysate Increases Amino Acid Uptake, mTORC1 Signaling, and Protein Synthesis in Skeletal Muscle of Healthy Young Men in a Randomized Crossover Trial. J Nutr [Internet]. 2019 [cited 2025 Apr 7]; Available from: https://consensus.app/papers/whey-protein-hydrolysate-increases-amino-acid-uptake-moro-brightwell/f58b008b86a550c3b350d03ee9b2b30b/
106. Bo Y, Liu C, Ji Z, Yang R, An Q, Zhang X, et al. A high whey protein, vitamin D and E supplement preserves muscle mass, strength, and quality of life in sarcopenic older adults: a double-blind randomized controlled trial. Clin Nutr. 2019;38(1):159–64.
107. Nasimi N, Sohrabi Z, Nunes E, Sadeghi E, Jamshidi S, Gholami Z, et al. Whey protein supplementation with or without Vitamin D on sarcopenia-related measures: a systematic review and meta-analysis. Adv Nutr. 2023;14:762–73.
108. Li M, Zhang F, Luo HY, Quan Z, Wang YF, Huang L, et al. Improving sarcopenia in older adults: a systematic review and meta-analysis of randomized controlled trials of whey protein supplementation with or without resistance training. J Nutr Health Aging [Internet]. 2024 [cited 2025 Apr 7];28 4. Available from: https://consensus.app/papers/improving-sarcopenia-in-older-adults-a-systematic-review-li-zhang/f9c68aa960a356bc8fb31dd16f76ef4e/
109. Finger D, Goltz FR, Umpierre D, Meyer E, Rosa LHT, Schneider C. Effects of protein supplementation in older adults undergoing resistance training: a systematic review and meta-analysis. Sports Med. 2015;45:245–55.
110. Kirwan RP, Mazidi M, Garcia CR, Lane KE, Jafari A, Butler T, et al. Protein interventions augment the effect of resistance exercise on appendicular lean mass and handgrip strength in older adults: a systematic review and meta-analysis of randomized controlled trials. Am J Clin Nutr. 2022;115(3):897–913.
111. Cornish S, Cordingley DM, Shaw KA, Forbes S, Leonhardt TPM, Bristol A, et al. Effects of Omega-3 Supplementation Alone and Combined with Resistance Exercise on Skeletal Muscle in Older Adults: A Systematic Review and Meta-Analysis. Nutrients [Internet]. 2022 [cited 2025 Apr 7];14. Available from: https://consensus.app/papers/effects-of-omega3-supplementation-alone-and-combined-with-cornish-cordingley/160c718394ef5d2e9049a2582579ef13/
112. Camargo JBD de, Oliveira AF de. Protein supplementation for strength and functionality in older adults: Is there still any doubt? A brief update review. J Aging Phys Act. 2022;1–8.
113. Kakigi R, Naito H, Ogura Y, Kobayashi H, Saga N, Ichinoseki-Sekine N, et al. Heat stress enhances mTOR signaling after resistance exercise in human skeletal muscle. J Physiol Sci. 2011;61(2):131–40.
114. Jacko D, Schaaf K, Masur L, Windoffer H, Aussieker T, Schiffer T, et al. Repeated and interrupted resistance exercise induces the desensitization and re-sensitization of mTOR-related signaling in human skeletal muscle fibers. Int J Mol Sci. 2022;23(10):5431.

115. Lundberg TR, Feuerbacher JF, Sünkeler M, Schumann M. The effects of concurrent aerobic and strength training on muscle fiber hypertrophy: a systematic review and meta-analysis. Sports Med. 2022;52(10):2391–403.
116. Perishable. When to Consume Protein for Maximum Muscle Growth [Internet]. 2023 [cited 2025 Apr 7]. Available from: https://www.usada.org/spirit-of-sport/when-consume-protein-muscle-growth/
117. Montull L, Slapšinskaitė-Dackevičienė A, Kiely J, Hristovski R, Balagué N. Integrative proposals of sports monitoring: subjective outperforms objective monitoring. Sports Med - Open. 2022;8(1):41.
118. Cannataro R, Cione E, Bonilla DA, Cerullo G, Angelini F, D'Antona G. Strength training in elderly: An useful tool against sarcopenia. Front Sports Act Living [Internet]. 2022 Jul 18 [cited 2025 Apr 7];4. Available from: https://www.frontiersin.org/journals/sports-and-active-living/articles/https://doi.org/10.3389/fspor.2022.950949/full
119. Morley JE, Abbatecola AM, Argiles JM, Baracos V, Bauer J, Bhasin S, et al. Sarcopenia with limited mobility: an international consensus. J Am Med Dir Assoc. 2011;12(6):403–9.
120. Cruz-Jentoft AJ, Bahat G, Bauer J, Boirie Y, Bruyère O, Cederholm T, et al. Sarcopenia: revised European consensus on definition and diagnosis. Age Ageing. 2019;48(1):16–31.
121. Evans WJ, Guralnik J, Cawthon P, Appleby J, Landi F, Clarke L, et al. Sarcopenia: no consensus, no diagnostic criteria, and no approved indication—How did we get here? GeroScience. 2024;46(1):183–90.
122. James JJ, Klevenow EA, Atkinson MA, Vosters EE, Bueckers EP, Quinn ME, et al. Underrepresentation of women in exercise science and physiology research is associated with authorship gender. J Appl Physiol Bethesda Md 1985. 2023;135(4):932–42.
123. Colenso-Semple LM, McKendry J, Lim C, Atherton PJ, Wilkinson DJ, Smith K, et al. Menstrual cycle phase does not influence muscle protein synthesis or whole-body myofibrillar proteolysis in response to resistance exercise. J Physiol. 2025;603(5):1109–21.
124. Galmes-Panades AM, Konieczna J, Abete I, Colom A, Rosique-Esteban N, Angeles Zulet M, et al. Lifestyle factors and visceral adipose tissue: results from the PREDIMED-PLUS study. Vol. 14, PLoS ONE; 2019.
125. Gabbett TJ. The training—injury prevention paradox: should athletes be training smarter and harder? 2016 Mar 1 [cited 2025 Apr 7]; Available from: https://bjsm.bmj.com/content/50/5/273
126. Kalkhoven JT, Watsford M. Mechanical Contributions to Muscle Injury: Implications for Athletic Injury Risk Mitigation. In 2020 [cited 2025 Apr 7]. Available from: https://osf.io/a5um4
127. Schumann M, Feuerbacher JF, Sünkeler M, Freitag N, Rønnestad BR, Doma K, et al. Compatibility of concurrent aerobic and strength training for skeletal muscle size and function: an updated systematic review and meta-analysis. Sports Med Auckl Nz. 2022;52(3):601–12.
128. Huiberts RO, Wüst RCI, van der Zwaard S. Concurrent strength and endurance training: a systematic review and meta-analysis on the impact of sex and training status. Sports Med. 2024;54(2):485–503.
129. Azizan A. Exploring the role of social media in mental health research: a bibliometric and content analysis. J Scientometr Res. 2024;13(1):01–8.

Publisher's Note