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Collagen Peptide Supplementation and Musculoskeletal Performance: A Systematic Review and Meta-Analysis

Kollagenpeptid-Supplementierung und muskuloskelettale Leistungsfähigkeit: Eine systematische Übersichtsarbeit und Meta-Analyse

REVIEW

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Summary

› **Problem:** There is a growing body of research investigating a variety of parameters affected by collagen peptide (CP) supplementation during structured exercise programs. The aim of this review is to focus on the musculoskeletal performance outcomes potentially affected by CP intake in healthy adults.

› **Methods:** A comprehensive literature search using defined MeSH terms was conducted in four databases (PubMed, Web of Science, EBSCO and Cochrane) by two independent reviewers. The resulting studies were used for systematic review and a random-effects meta-analysis.

› **Results:** A total of 13 studies were included in this review. Two primary study objectives were identified, categorizing studies into those focusing on a potential effect of CP intake on adaptation to training stimuli and those focusing on recovery from training stimuli. Nine of these studies were used for in-depth meta-analysis. Of the 55 performance parameters extracted, 48 were unaffected by additional CP intake. Furthermore, the meta-analysis revealed no significant effect of CP on strength-related performance parameters (SMD=0.079 [-0.120 to 0.273], p=0.445).

› **Discussion:** The studies included show a high degree of homogeneity in most methodological aspects and have a low risk of biased results, which supports the validity of the results found. Nevertheless, this result represents the current state of scientific knowledge.

› **Conclusion:** The qualitative and quantitative analysis of the available studies suggests the ineffectiveness of CP supplementation in addition to exercise to further improve musculoskeletal performance.

KEY WORDS:
Low-Quality Protein, Hydrolyzed Collagen, Recreational Athletes, Adaptation, Recovery

Introduction, Problems and Aim

In the realm of competitive sports, optimizing the physiological adaptations resulting from training is a paramount objective for practitioners aiming to enhance athletic performance. Specifically, the plastic and highly adaptable human skeletal muscle tissue stands as the focal point of interest within the training regimens of coaches and athletes. Skeletal muscle experiences a daily turnover rate of approximately 1-2% (17), with mechanical stimuli, such as resistance-type exercise, having the greatest effect on modulating this rate and consequently provoking alterations in both the structural composition and overall mass of skeletal muscle (49). From a nutritional perspective, proteins, whether derived from daily dietary intake or obtained through protein supplements, serve a dual role in supporting these adaptations. Firstly, they provide the essential building blocks required for muscle tissue adaptation. Secondly, they function as signaling molecules, further amplifying the anabolic response triggered by training stimuli (40). Therefore, sports nutrition, with a particular emphasis on protein consumption, has emerged as a pivotal component in both recreational and elite sports settings over the past two decades (24). Proteins can be categorized based on their quality, with high-quality proteins being those rich in essential amino acids and easily digestible. Such proteins are favored for their capacity to maximize anabolic responses (7, 34). Conversely, proteins like collagen are considered low-quality due to their lower essential amino acid content and deficiency in tryptophan (37). Interestingly, there is a growing body of research suggesting potential benefits of Collagen Peptides (CP) in relation to training capacity, recovery, muscle soreness, and injury management, despite their classification as low-quality proteins (32). Collagen, the predominant structural protein found in the connective tissue of muscles, tendons, and ligaments (14), facilitates force transmission generated by myofibrillar proteins to enable movement (42). Supplementation with CP may potentially augment the availability of specific non-essential amino acid precursors, hypothetically supporting training-induced adaptation of collagenous tissues as mentioned. This, in turn, could potentially contribute to enhanced muscular strength, thus provi- ›

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Table 1

Studies evaluating the effects of collagen supplementation and structured physical activity on the adaptation of musculoskeletal performance outcomes. RCT=randomized controlled trial; RET=resistance exercise training; BFR=blood flow restriction; CP=collagen peptides; COL=collagen supplementation group; PLA=placebo supplementation group; CON=control group; MVC=maximal voluntary isometric contraction; MVT=maximal voluntary torque; 1RM=one repetition maximum; LT=lactate threshold; IAT=individual anaerobic threshold; p-values=result of statistical interaction effect (group×time); ↔=not different; ↑=increased; ↓=decreased. Values are means±SD.

STUDY	PARTICIPANTS	DURATION & DESIGN	DOSAGE	PERFORMANCE OUTCOMES
Balshaw et al., 2022 (4)	39 recreational men (18-40y); 25.7±4.3y, 74.6±11.7kg, 1.79±0.08m	105 days (15 wk) RCT , lower body RET (3x/~15-20min/week) COL: n=19, PLA: n=20	15g/d CP vs. maltodextrin	↔ in knee extension MVT changes between groups (p=0.596) ↔ in knee flexion MVT changes between groups (p=0.671) ↔ in knee extension 1RM changes between groups (p=0.743) ↔ in changes of absolute and relative knee extension isometric explosive strength at various time points between groups (p≥0.05, respectively)
Centner et al., 2019 (6)	30 recreational men (≥50y) 60.1±7.6y, 84.5±15.2kg, 1.78±0.06m	56 days (8 wk) RCT, low-load lower extremity RET (3x~6.5min/week) Low-load BFR + COL: n=11, Low-load BFR + PLA: n=11, CON (no training but CP supplementation): n=8	15g/d CP vs. silicon dioxide	↔ in leg press MVC changes between groups (p=0.247)
Jendricke et al., 2019 (21)	77 untrained premenopausal women (18-50y)	84 days (12wk) RCT, whole body RET (3x60min/week) COL: n=40, PLA: n=37	15g/d CP vs. silicon dioxide	↔ in leg press MVC changes between groups (p>0.05) ↑ in changes of hand grip MVC in COL compared to PLA (p<0.05)
Jendricke et al., 2020 (22)	59 recreationally active female runners (18-40y)	84 days (12 wk) RCT, concurrent training (3x~80min/week) COL: n=28, PLA: n=31	15g/d CP vs. silicon dioxide	↑ in running distance during a time trial in COL compared to PLA (p<0.05) ↔ in changes of velocity at LT and IAT between groups (p>0.05, respectively) ↔ in back squat 1RM and lower limb muscular endurance changes between groups (p>0.05)
Jerger et al., 2022 (24)	27 recreational men (18-40y) 26.3±4.0y, 77.1±13.4kg, 1.80±0.09m	98 days (14 wk) RCT , high-load calf RET (3x~-22min/week) COL: n=13, PLA: n=14	5g/d CP vs. maltodextrin	↔ in plantar flexion MVT changes between groups (p=0.629)
Kirmse et al., 2019 (27); Oertzen-Hagemann et al., 2019 (36)	57 RET experienced men; 24.4±3.3y, 78.8±7.4kg, 1.84±0.06m	84 days (12wk) RCT, whole body RET (3x60min/week) COL: n=29, PLA: n=28	15g/d CP vs. silicon dioxide	↔ in leg extension MVC changes between groups (p=0.477) ↔ in changes of squat, deadlift, bench press, and bent over row 1RM between groups (p=0.054, p=0.576, p=0.474, p=0.768, respectively)
Lis et al., 2022 (29)	48 male collegiate athletes (18-25 y); 18.8±2.0y, 85.8±18.3kg, 1.80±0.16m	21 days (3 wk) RCT, maximal power/RFD program (3x/week) + subjects regular sport specific team training, COL: n=23, PLA: n=25	20g/d CP+50 mg vitamin C daily vs. maltodextrin	↔ in squat MVC between groups (p=0.56) ↑ in changes of squat RFD from baseline to test 3 in COL compared to PLA (student´s t test result including outlier: p=0.036) ↔ in CMJ height between groups (p=0.60) ↑ in CMJ eccentric impulse in COL compared to PLA (p=0.03) ↔ in squat jump performance between groups (all parameter, p>0.05)
Nunez-Lisboa et al., 2021 (35)	9 recreational male triathletes; 32.5±4.1y, 68.4±5.7kg, 1.72±0.05m	28 days (4 wk) RCT, 4x100m sprints (3x/week), COL: n=5, PLA: n=4	12g/d CP on sprint days vs. maltodextrin	↔ in $\dot{V}O_2$max changes between groups (p=0.641) ↔ in bouncing mechanisms of running between groups (p>0.05)
Zdzieblik et al., 2021 (50)	97 overweight and untrained men (30-60y); 49.6±7.0y, 97.8±10.6kg, 1.79±0.06m	84 days (12wk) RCT, whole body RET (3x60min/week) COL: n=30, Whey protein: n=36, PLA: n=31	15g/d CP vs. whey isolate vs. maltodextrin	↔ in leg press MVC changes between all groups (p=0.444)

ding a rationale for the growing number of studies and adoption of CP supplementation among athletes (13). Previous systematic and narrative reviews have examined the effects of CP ingestion on various physiological outcomes, including body composition, collagen synthesis, and joint pain relief (systematic) (25); musculoskeletal connective tissue remodeling (narrative) (18); potential relevance in sports nutrition (systematic) (27); and musculoskeletal outcomes (not systematic) (12). Nevertheless, these reviews only briefly touched upon performance outcomes and did not delve into them extensively, as they were not the primary focus. Furthermore, no quantitative analysis through meta-analysis has been applied to the existing studies to date. Hence, the primary objective of this systematic review and meta-analysis is to provide an updated and comprehensive systematic review of the scientific literature, focusing exclusively on the impact of CP supplementation on musculoskeletal performance outcomes in healthy individuals.

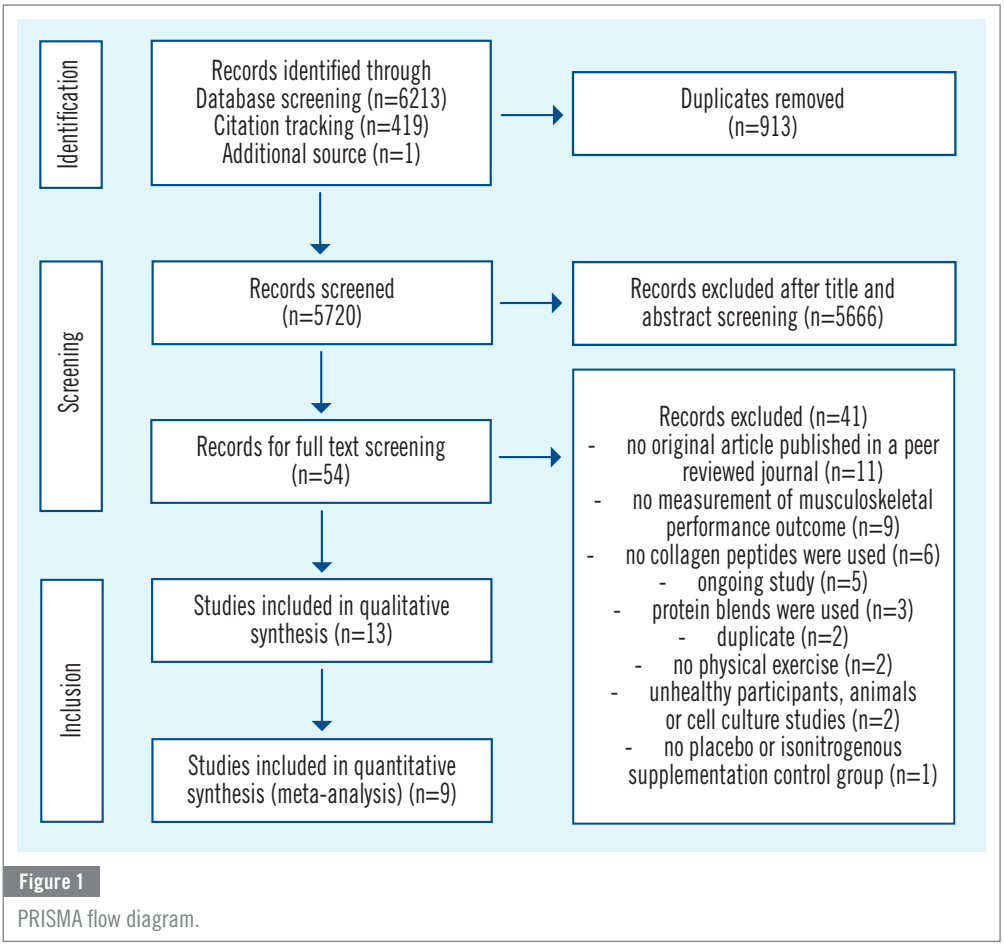

Figure 1
PRISMA flow diagram.

Material and Methods

This review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (33). The review process was registered and published on Prospective Register of Systematic Reviews (PROSPERO) (www.crd.york.ac.uk/PROSPERO) website with registration number CRD42022322034.

Data Sources and Search Strategy

To identify relevant published studies until 17th June 2022, we used the online databases: PubMed, Web of Science, EBSCO, and Cochrane. Search strategies included the following terms: collagen OR collagen peptide OR collagen supplementation OR gelatin/gelatine OR low-quality protein AND exercise OR 1RM OR MVC OR MVIC OR jump OR strength OR muscle strength OR performance OR aerobic exercise OR training OR nutritional supplement OR recovery OR damage. If possible, the filters „clinical trial" and „randomized controlled trial" were selected. All records were manually and independently screened for relevance by MK and VH using the Covidence® software (10). We performed forward and backward screening of references and citations of records that passed the full-text screening to identify as many relevant studies as possible.

Eligibility Criteria

Studies were only included if they fulfilled or included all of the following criteria or information based on the Participants, Interventions, Comparators, Outcomes and Study design (PICOS) framework (33).

Participants: Healthy human participants over the age of 18.
Interventions: Intake of CP / gelatin (no blends) in combination with structured physical activity or highly demanding exercise.
Comparators: A placebo or isonitrogenous supplement control group in combination with an equally structured physical activity protocol as the intervention group.
Outcomes: Performance parameters related to the musculoskeletal system (maximum voluntary isometric contraction (MV(i)C), maximum voluntary torque (MVT), one repetition maximum (1RM), jumps, aerobic tests). The applied physical activity / exercise protocol.
Study Design: Only peer-review and full-text articles with randomized controlled trials were eligible.

Data Extraction and Synthesis

The lead author extracted the data from the identified articles. VH and RS double checked the final extraction for accuracy. The following data were extracted for qualitative synthesis: lead author, year of publication, number and characteristics of participants included for statistical analyses, duration and general information about the study design and applied exercise modality, dosage and type of CP and of the placebo, key findings of the performance assessments. For the quantitative synthesis, data from the following performance tests were predefined as inclusion criteria for the meta-analysis and prioritized in advance as follows: 1. MV(i)C/MVT, 2. 1RM, 3. jumps. Additional data extraction for meta-analysis included the following outcomes: pre and post means and standard deviations (sd) of prioritized outcomes. When data was not presented in a table or text, attempts were made to contact the authors. If this was unsuccessful, the data was plotted using WebPlotDigitizer (Web Plot Digitizer, V.3.11. Texas, USA: Ankit Rohatgi, 2017). Further ›

data, such as multiple time points or additional groups consuming other protein sources, were not considered. The changes in mean (Δmean) between time points were calculated for each group. Due to different numbers of participants between groups within studies, we calculated the pooled SD (SDp) of the pre values using a known formula (11). Heterogeneity was assessed using the X^2 statistic, to determine whether observed differences in results could be attributed to chance alone (19). The degree of heterogeneity among the effect sizes of the studies was determined by calculating I 2, which was defined as follows: 25% - low; 50% - medium; 75% - high degree of heterogeneity (5, 16). Heterogeneity was deemed statistically significant when the p-value derived from the X^2 test was less than 0.1, or when the I 2 test produced a value equal to or greater than 50%.

Effect Sizes

The excel spreadsheet „free effect sizes and confidence intervals (esci)" was used to perform a random-effects meta-analysis (11) for change in performance outcomes. This involved estimating standardized mean differences (Cohen´s $d_{unbiased}$), 95-% confidence intervals (CI), and study weight from differences of Δmean between groups and sdp (11). A forest plot was employed to visualize the respective effect sizes and their 95-% CIs.

Risk of Bias

The revised Cochrane risk-of-bias (RoB 2.0) was used to assess the quality of the included studies (46). The quality was assessed independently by MK and RS, with subsequent discussions about the results, until agreement was reached.

Results

Study Selection

A total of 5,720 studies underwent initial screening based on their titles and abstracts. Among these, 54 were identified as potentially meeting the inclusion criteria and underwent full-text screening. Out of these, 41 studies did not meet the criteria during the full-text examination, leaving 13 studies eligible for inclusion in the systematic review (figure 1). It is worth noting that two of these studies reference the same pool of subjects (26, 36). However, it should be noted that Oertzen-Hagemann et al. (36) only included subjects from the first part of the study, from whom biopsies were taken for proteome analysis. On the other hand, Kirmse et al. (26) focused on performance outcomes, covering both parts of the study and utilizing the complete set of successfully included subjects. Therefore, these studies are listed together, but the data were extracted from Kirmse et al. (26).

We identified two overarching study objectives for the exercise and CP intake protocols in the studies, according to which we have organized the structure of the presentation of results: (i) studies that examined adaptation capacity (n=10, table 1), and (ii) studies that examined recovery capacity (n=3, table 2) of specific musculoskeletal performance parameters.

Qualitative Synthesis: Studies Examining and Adaptation Capacity

Population: Results from ten studies and 399 healthy subjects (including 136 women) with a mean age of 33.7±12.8 y (lowest: 18.8 y; highest: 60.1 y) from 20 groups were included. The studies included the following subject classifications and accumulated participants numbers: Three studies with recreational men (n=88) (4, 6, 23), two studies with resistance type exercise training (RET) experienced men (n=57) (26, 36), and one study each with untrained premenopausal women (n=77) (20), active female runners (n=59) (21), collegiate male athletes (n=48) (29), overweight untrained men (n=61) (50), and recreational male triathletes (n=9) (35).

Intervention: The total duration of all ten included studies with a focus on potential adaptation capacity changes is 644 days (mean: 71.6±28.2 d; lowest: 21 d; highest: 105 d). All studies used enzymatically pre-treated, i.e. hydrolyzed collagen peptides (4x Bodybalance®, GELITA AG (20, 26, 36, 50); 1x Tendoforte®, GELITA AG (23); 1x mixture of Bodybalance® and Tendoforte®, GELITA AG (4); 1x PeptENDURE (planned product), GELITA AG (21); 1x Gelatine, Great Lakes (35); 1x collagen sponsored by Collagen Research Institute (Kiel, Germany) (6) and 1x unknown (29). The CP were ingested daily in nine studies with seven studies using dosages of 15g (4, 6, 20, 21, 26, 36, 50), one study used 5g (23), and one study used 20g with additional 50mg vitamin C (29). In one study, the 15g supplement consisted of 12g of CP taken three times per week (35). The CP was ingested immediately and up to 60 minutes after training in seven studies (4, 6, 20, 23, 26, 36, 50), 60 minutes before the training in two studies (29, 35), and in one study, half of the supplement (7.5g) was taken two hours before and the other half immediately after training (21). All supplements were dissolved in water (lowest: 250 ml; highest: 500 ml). The following training regimens were used: lower body (4, 6, 23) and whole body RET (20, 26, 50), and one study each with concurrent training (21), power training (29), and sprint training (35). The mean of the maximum number of sets per exercise and studies using lower or whole body RET ranged from 3 to 4 with a range from 6 to 15 repetitions per set. Here, the training intensity was derived from the 1RM and was 70-85%, corresponding to 6-15 repetitions. Centner et al. (6) also performed a RET for the lower body, but used different intensities because a cuff was used during training to restrict blood flow. Their subjects performed 30 repetitions in the first set and 15 repetitions in the following three sets, corresponding to 20-30% of determined 1RM. The concurrent training of Jendricke et al. (21) consisted of body weight exercises with 3 sets of a maximum of 30 repetitions per set at the end of the investigation and an additional 1-hour run at a maximum of 90% of the participants' velocity at individual anaerobic threshold. The power training of Lis et al. (29) included plyometric and ballistic exercises with a range of 2-5 sets and 10 repetitions per set. Nunez-Lisboa et al. (35) used four 100 m sprints per training session to provide adaptation stimuli. In almost all studies, progressive increases in training intensity were sought by manipulating the number of sets (4, 29), loads (4, 6, 23, 26, 50), or repetitions (4, 20, 21, 23, 50).

Comparator: All groups completed the identical testing and training procedure. The placebo supplement consisted of maltodextrin in four (4, 23, 29, 35) and of silicon dioxide in six (6, 20, 21, 26, 36, 50) studies.

Outcome: Twenty distinct test procedures are presented, with certain ones being employed across multiple studies. Thus, the results of a total of 24 paired data sets are shown. A tabular presentation of the performance outcomes can be found in table 1. In 20 tests, no significant group differences over time were found in the applied isometric maximum strength tests (4, 6, 20, 23, 26, 29, 36, 50), dynamic maximum strength tests (4, 21, 26, 36), individually calculated speeds at specific lactate thresholds (21), $\dot{V}O_2$ (35), and jumping performance (29). Group differences in musculoskeletal performance-related parameters were found only in four tests, from three studies (20, 21, 29). The HCP supplementing participants of Jendricke et al. (20) exhibited a significantly greater increase in handgrip strength ($p<0.05$, $d=0.63$) compared to the placebo group, while no group differences were observed in changes of leg press MVC. In another study conducted by

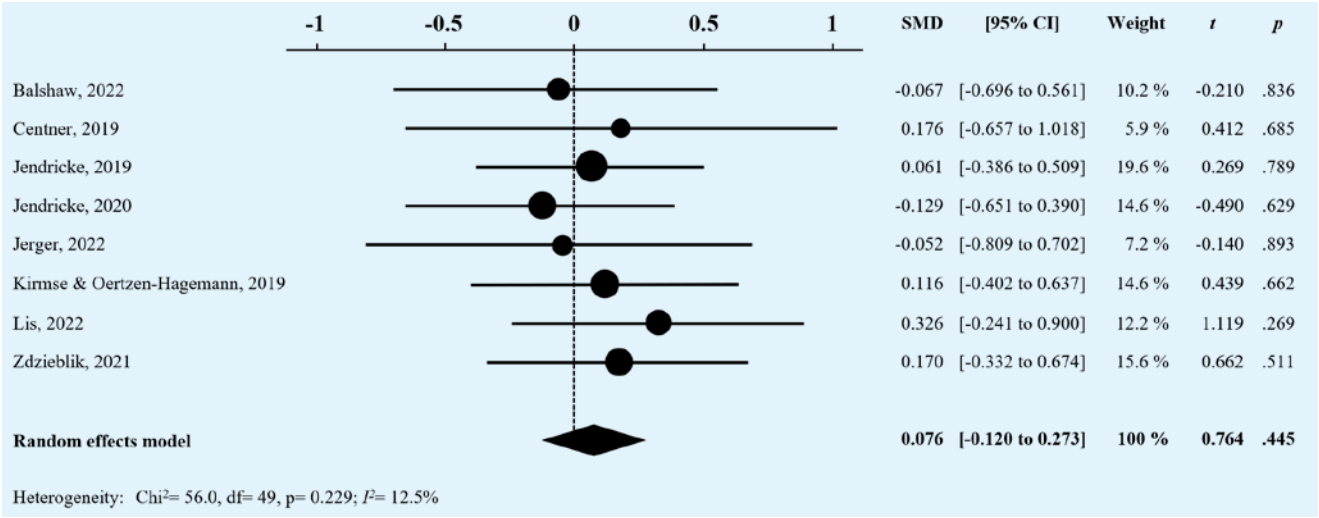

Figure 2

The forest plot presents the outcomes of a random-effects meta-analysis, displaying the standardized mean difference (SMD) alongside 95% confidence intervals (CIs) for the effects of collagen peptide supplementation on strength-related performance parameters. Each study is represented by a circle in the plot, denoting the mean difference in the intervention effect, with a horizontal line extending across it to represent the lower and upper bounds of the 95% CI. The size of each circle indicates the study's relative weight in the meta-analysis. The diamond represents the pooled mean difference.

Jendricke et al. (21), a time × group interaction effect ($p<0.05$; $d=0.155$) was observed, indicating a higher increase in running distance during a time trial among participants consuming HCP in contrast to the placebo group. Lastly, despite the absence of significant differences in squat MVC and maximal countermovement jump (CMJ) height between the groups in the study by Lis et al. (29), the HCP group, with one notable outlier, displayed a greater increase in rate of force development (RFD) during squats ($p=0.036$) and a greater maximal impulse during the eccentric phase of the CMJ ($p=0.03$) in comparison to the control group.

Study Design: All studies used the gold standard (15) study design (RCT) with parallel groups. In addition to predetermined inclusion criteria, both researchers and subjects were blinded for treatment in all included studies.

Studies Examining Recovery Capacity:

Population: The study included 51 healthy male subjects from three investigations with a mean age of 23.9±0.9 y (lowest: 22.6 y; highest: 24.6 y) from six groups. The subject classifications included recreational active men (n=24)) (9) and resistance exercise trained (RET) experienced men (n=27) (41, 43).

Intervention: The three included studies focused on changes in recovery capacity over a total duration of 32 days (mean: 10.7±0.9 days; lowest: 10 days; highest: 12 days). Hydrolyzed CP was used in all studies (2x Peptan®, Rousselot (9, 43)); 1x Collagen Peptides, Vital Proteins (41). Clifford et al. (9) conducted a study in which participants underwent a seven-day pre-load phase. During this phase, they consumed 10g of HCP with water and 50 ml of Ribena Light (containing 80 mg of vitamin C) twice daily. Following this, participants were subjected to 150 drop jumps to induce exercise-induced muscle damage (EIMD). The supplement was taken before the EIMD protocol and subsequent performance testing, and with dinner on days 8 and 9. The last dose was taken 40 minutes before testing on day 10. Prowting et al. (41) instructed their subjects to consume 15g of HCP dissolved in water during dinner for 12 consecutive days. On day 7, the subjects performed 100 drop jumps to induce EIMD. Rindom et al. (43) employed a cross-over design in which the subjects consumed 25g of both HCP and whey protein twice daily for one week each. During the training weeks, the participant completed four intense full-body training sessions. Supplements were ingested 30 minutes before and immediately after training, as well as at comparable time points on non-training days. The training regimen consisted of 3-5 sets of 12 repetitions each for leg press, bench press, pull-ups, squats, and knee extensions. Performance tests were conducted at the end of each training week to assess fatigue and recovery ability.

Comparator: In their studies, Clifford et al. (9) and Prowting et al. (41) subjected their groups to the same damaging protocol and testing procedure. However, Rindom et al. (43) exposed their participants to both the placebo and the HCP supplement. The placebo used in the studies was maltodextrin (9), isoenergetic cornstarch (41), and whey protein (43).

Outcome: The three studies included a total of five distinct test procedures for hypothesis testing. CMJ's and MVC's were repeatedly applied across multiple studies and subjected to repetitive testing over several consecutive days to evaluate recovery capacity. This resulted in a total of 31 paired data sets, excluding any data from pretesting sessions. Table 2 presents the performance outcomes in a tabular format. In 28 datasets, most CMJ testing (9, 41, 43), isometric strength testing (9, 41, 43), and anaerobic and aerobic performance testing (43) showed no group differences over time. However, three CMJ datasets (one per study) showed group differences, indicating accelerated recovery in the CP group compared to the placebo group at specific time points. Rindom et al. (43) found a significant decrease in performance at 3 hours ($p<0.05$), while Prowting et al. (41) reported a significant decrease at 24 hours ($p=0.001$, $ES=0.32$), and Clifford et al. (9) found a significant decrease at 48 hours ($p=0.04$) following the EIMD protocol.

Stud design: The studies included in this analysis used the gold standard study design, which is the randomized controlled trial (RCT)) (15). Two of the studies used parallel groups (9, 41), while one study used a crossover design (43). In addition to predetermined inclusion criteria, both researchers and subjects were blinded to treatment in all three studies.

Risk of Bias

Except for one study, the RoB 2.0 tool identified a low risk of bias in each of the five domains, as well as in the overall ›

Table 2

Studies evaluating the effects of collagen supplementation on the recovery of musculoskeletal performance outcomes after short-term strenuous exercise. RCT=randomized controlled trial; CP=collagen peptides; CMJ=counter movement jump; DJ=drop jumps; EIMD=exercise induced muscle damage; COL=collagen supplementation group; PLA=placebo supplementation group; MVC=maximal voluntary isometric contraction; RFD=rate of force development; p-values=result of statistical interaction effect (group×time); ↔=not different; ↑=increased.

STUDY	PARTICIPANTS	DURATION & DESIGN	DOSAGE	PERFORMANCE OUTCOMES
Clifford et al., 2019 (9)	24 recreationally active men	10 days RCT: 150 DJ at day 8, testing at day 9 and 10, COL: n=12, PLA: n=12	20g/d CP daily vs. maltodextrin	↑ in CMJ height 48 h post DJ in COLcompared to PLA (p=0.040) ↔ in leg extension MVC post DJ (0, 24, 48 h; p>0.05)
Prowting et al., 2020 (41)	15 resistance trained men	12 days RCT, 5x20 DJ at day 7, testing at day 8, 9, and 12, COL: n=7, PLA: n=8	15g/d CP daily vs. cornstarch	↑ in CMJ height 24 h post DJ (day 8) in COL compared to PLA (p<0.001) ↔ in knee extension MVC of both legs between groups (left: p=0.621; right: p=0.141)
Rindom et al., 2016 (43)	12 resistance trained men; 24.6±2.1y, 79.4±9.3kg, 1.84±0.06m	2x block a 5 days crossover, per block: 4x RET, testing prior to and 3, 24, and 48 h after block, 1x block with CP + 1x block with Whey supplementation, n=6 each group	25g/d CP vs. whey	↔ in knee flexor and extensor MVC changes between blocks (3, 24, and 48 h post; p>0.05, respectively) ↑ in CMJ height at 3 h post Whey block compared to COL block (p<0.05) ↔ in mean and peak anaerobic power changes between blocks (3, 24, and 48 h post; p>0.05) ↔ in aerobic endurance performance changes between blocks (p=0.84)

assessment, in 12 studies. In the study of Centner et al. (2019) (6), the prescribed methods were not consistent with the reported outcomes and were classified as high risk in the respective domain, with some concerns as the overall classification (see supplementary table 3 online).

Quantitative Synthesis

To avoid drawing erroneous conclusions from the limited number of studies that investigated recovery capacity through CP and the differences within the methodologies of the studies (training methodology, duration, dosage, placebo, duration, outcomes), a conscious decision was made to refrain from conducting the meta-analytical calculation. Furthermore, the study conducted by Nunez-Lisboa et al. (35) was excluded because it did not use any of the predefined strength-related performance tests. Consequently, the final meta-analysis included 9 studies that exclusively investigated adaptation capacity through CP, most of which evaluated isometric maximal strength (4, 6, 20, 23, 26, 29, 36, 50), while one study evaluated dynamic maximal strength (21). The Chi2 test (χ^2=56.0, df=49; p=0.229) and I2 statistic (12.5%) suggest homogeneity among the included studies. After conducting the meta-analysis, the results show that CP supplementation has no significant effect on strength-related performance outcomes (SMD=0.079 [-0.120 to 0.273], p=0.445). Figure 2 provides a graphical representation of the meta-analytic findings.

Discussion

This review and meta-analysis analyzed the impact of collagen peptide (CP) intake during structured short-term or long-term training stimuli on musculoskeletal performance parameters. The overall qualitative analysis of 13 included studies and the in-depth quantitative meta-analysis of nine of these studies indicates that CP does not exert any clinical meaningful impact on both the long-term adaptation or short-term recovery of performance parameters.

This review syntheses data from studies involving a total of 450 participants, distributed among seven subgroups and both sexes, with an age range of means spanning from 18.8 to 60.1 years. The variability in participant characteristics could potentially impact the study results and, subsequently, the overall findings of this review. In the context of other reviews and meta-analyses involving different protein sources, it has been established that outcomes can be influenced by factors such as age and training status (7, 34, 48). Additionally, adjustable training parameters such as intensity, number of sets and repetitions, as well as the duration of the interventions can vary considerably, which may also affect the outcome (2, 47). The frequency of training also influences the study outcomes (44), which is consistent across all included long-term studies (3×/week). There is also consistency in the quantity of CP administered, with most studies using a daily dosage of 15 grams. This may be attributed to early work by Zdzieblik et al. (52), which may have subsequently influenced further research in this area. These observations arise from the dynamic and emerging nature of the relatively new research field. Therefore, this review should be considered as a snapshot of the existing literature, acknowledging the potential impact of diverse subject and training characteristics on the study outcomes.

Both qualitative and quantitative analyses of the studies included indicate that CP supplementation has no significant impact on short-term recovery or long-term adaptation of musculoskeletal performance parameters. It is important to note that none of the studies included demonstrated any adverse effects or disadvantages associated with CP supplementation. Additionally, gelatine, which is a hydrolyzed form of collagen, has been granted the 'Generally Recognized as Safe' (GRAS) status by the American Food and Drug Administration (FDA) since 1975. Therefore, it is widely accepted that CP itself, as well as the consumption of CP supplements, are generally safe and not commonly associated with adverse effects (28).

Upon closer examination of the limited instances where the CP group exhibits statistically significant and positive developments, it is apparent that six out of the seven results showing significant differences between the groups are prominently linked to assessments that involve movements characterized by reactive or explosive strength. These include the results of CMJs

(9, 41, 43), the eccentric phase during the CMJ and the rate of force development assessment during a squat (29), and running performance during a time trial (21). The increase in handgrip strength observed among the participants who consumed CP in Jendricke et al.'s (20) study cannot be attributed to the general category mentioned above and may be considered an exceptional or atypical outcome, possibly an outlier. However, it remains unclear whether CP has a positive impact on movements and exercises involving the stretch-shortening cycle. This uncertainty arises from a substantial body of research that has shown no discernible effects. To emphasize this, our analysis is based on a comprehensive set of 55 paired data sets, encompassing 48 instances where no significant effects were observed.

Most of the studies included in this analysis were conducted with rigorous scientific standards, as indicated by their low risk of bias (8, 46). However, in addition to the discrepancies between methodology and results pointed out by Centner et al. (6) it should also be noted that the investigators of the study from Lis et al. (29) had little influence on the training of their subjects. These participants in this study came from various sports backgrounds and mainly focused on their sport-specific training, with only a few elements of strength training included. However, this had no impact on the rating given by the RoB 2.0 tool. Additionally, evaluating the residual risk of bias helps to interpret the results of the other studies without any further concerns. It is important to acknowledge potential conflicts of interest, such as financial support, provision of supplements, or involvement in study design or manuscript composition, particularly if the individuals or companies involved stand to gain financially from the study's outcomes (30). Within the 13 studies we analyzed, these elements were identified in 11 cases, either individually or as combinations of multiple factors. Financial support (4, 9, 20, 21, 22, 26, 29, 36, 43, 50), contributions to study design (20, 22), provision of dietary supplements (6, 9, 26, 36, 50), and assistance with manuscript preparation (20, 22, 26, 36, 50) were provided by individuals or companies associated with the sale of CP or sports nutrition supplements in general. The authors of almost all studies declare no conflict of interest, except for one study that does not explicitly state so (29), although this can be assumed because the study's funding is presented transparently. It is important to note that the acknowledgment of potential conflicts of interest is not intended to cast doubt on the integrity of the authors, including ourselves. Here, the purpose is to examine prevailing practices in relevant studies and critique the current funding system. The primary emphasis should be on acquiring scientifically unbiased knowledge rather than profit-driven interests. Evidence suggests that financial ties, even if unintentionally, could potentially steer results towards more favorable overall conclusions (31). However, it is unlikely that significant bias exists when considering the results obtained within the context of the included studies.

Currently, the mechanisms responsible for any potential positive effects of additional CP intake during structured resistance type exercise training on musculoskeletal performance parameters are not yet fully understood. Although there are ongoing considerations, mostly from in vivo or in vitro models (18), and new studies emerging in this area, it is important to note that no definitive mechanism has been established. Zdzieblik et al. (51) conducted one of the initial studies on the effects of CP supplementation in conjunction with strength training, which reported significant increases in strength and body composition, particularly in sarcopenic subjects. However, subsequent research attempts have struggled to replicate these results, leading to significant skepticism within the scientific community (39). CP has a digestible indispensable amino acid score of 0, mainly because it lacks the essential amino acid tryptophan (38). Therefore, current data suggest that CP supplementation does not affect human skeletal muscle myofibrillar proteins (3, 37). Shaw et al. (45) conducted a study that observed elevated markers of procollagen type I N-terminal pro-peptide (PINP) in the blood of subjects who engaged in ballistic-plyometric exercise, specifically rope skipping, after CP ingestion. Elevated blood levels of PINP indicate an increased synthesis of connective tissue proteins. This finding indicates that CP intake may promote the production of connective tissue proteins, which could improve the structural integrity of tendons, ligaments, and other passive tissues. It is suggested that nutritional support for passive tissues, including increased synthesis of connective tissue, particularly collagen, as a result of CP intake during exercise, may contribute to improved musculoskeletal adaptations. This may improve the transfer of forces from actively contractile muscle cells through the connective tissue to the surrounding bone, ultimately leading to enhanced performance (1). However, recent studies have not shown a significant effect of CP on post-exercise muscle connective tissue protein synthesis (3, 37). Additionally, the comprehensive meta-analysis conducted in this study cannot support the hypothesis of increased performance parameters. However, to date, no research has investigated the impact of combined CP intake and exercise on the synthesis of connective tissue proteins in passive tissues that are rich in collagen, such as tendons. Previous studies have shown that prolonged resistance exercise training with daily CP intake resulted in morphological adaptations, including increased hypertrophy of the Achilles and Patella tendons (22, 23). Although these findings are interesting, they should be interpreted with caution as neither of the two studies showed a significant effect of CP supplementation on muscle strength. It is important to maintain objectivity and avoid overstating the potential implications of the results.

Conclusion

In summary, although the effects of CP supplementation on musculoskeletal performance parameters are still being investigated, there is currently no established mechanism to explain its potential benefits. Further research is needed to clarify the precise mechanisms and conditions under which CP supplementation may influence musculoskeletal adaptations or recovery, which may lead to improved performance. This review presents an extensive analysis of the outcomes obtained from different performance assessments. The consumption of collagen peptides did not affect most of the parameters. Therefore, the few significantly different findings can currently be considered inconsequential. Nonetheless, these findings provide valuable insights for future research. Finally, it is important to emphasize that, despite considerable methodological disparities, the current body of research does not support the use of collagen peptides to enhance short- or long-term athletic performance.

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Funding and conflict of interest

PP received financial support from the Collagen Research Institute, Germany, for previous studies that have already been concluded and published, and which are also included into this review (26, 36). This collaboration was concluded with the publication of those studies in 2019 and is unrelated to the present review and meta-analysis. Therefore, all authors confirm that there is no conflict of interest.

Competing interests

All authors have completed the ICMJE Uniform Disclosure Form at www.icmje.org/coi_disclosure.pdf and declare: no support from any organization for the submitted work; no financial relationships with organizations that may have an interest in the submitted work in the past three years; no other relationships or activities that may have influenced the submitted work.

Ethical Approval

Not required for systematic reviews.

Summary Box

This study examined the effects of collagen peptide supplementation on performance-related parameters in healthy recreational individuals. Most of the performance tests showed no significant changes with the additional supplement intake. Furthermore, the statistical meta-analysis revealed no effect of collagen peptide ingestion on either isometric or dynamic maximal strength. We assume that if the daily protein requirements are met through a balanced diet, additional collagen peptides do not enhance athletic performance.

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