# COLLAGEN, VITAMIN C AND DIETARY PROTEIN

## What human studies actually measure - and what they do not prove

| 5 levels | 2-3 g/day | No known max |
|---|---|---|
| Evidence ladder | Common whole-body turnover estimate | Human collagen production ceiling |

### Central conclusion

Collagen supplementation is biologically plausible and has several positive tendon-structure trials, but the evidence changes meaning depending on whether a study measured blood amino acids, serum PINP, tissue fractional synthesis rate, or the tendon itself. The report therefore ranks every major study by measurement directness.

### What this report corrects

PINP is a systemic type-I procollagen formation marker, not a direct measurement of collagen deposited in a tendon. Acute 15-30 g dose-response studies belong in the PINP tier.

### What this report calculates

A transparent mass-balance model links a 2-3 g/day turnover estimate to glycine, proline and lysine precursors, then compares raw chicken, whey, collagen, pea and soy.

### What the vegan evidence says

No direct tendon-FSR comparison of vegans and omnivores was found. Existing data concern bone-turnover markers and do not show that avoiding dietary collagen stops endogenous collagen production.

### Best-supported practical claim

Collagen plus vitamin C may enhance tendon remodeling when paired with progressive high-intensity loading. It is an adjunct, not a substitute for complete dietary protein or loading.

*Technical synthesis prepared from the supplied evidence decks plus primary human research and current systematic reviews.*

EXECUTIVE SUMMARY

# The answer depends on what was measured

A study can be technically correct and still be unable to answer the question people think it answered.

| | |
|---|---|
| **Blood amino acids**<br>Show digestion and availability. They do not show that collagen synthesis started, where amino acids went, or whether a tendon changed. | **Serum PINP**<br>Shows systemic formation/processing of type-I procollagen. It is useful mechanistically, but strongly reflects bone and is not tendon-specific. |
| **Tissue FSR**<br>Stable isotopes plus biopsy show new label entering a measured tissue-protein fraction. This is direct short-term synthesis, but still gross synthesis rather than net gain. | **Tendon structure/function**<br>CSA, stiffness and Young's modulus are closer to the real target. They take weeks/months and still do not isolate which molecular mechanism caused the adaptation. |

- **The 30 g whey / 25+5 / 20+10 / 15+15 study:** measured plasma amino-acid availability only. Fifteen grams collagen produced the highest glycine exposure; five grams was enough to prevent the post-exercise glycine decline. No collagen synthesis was measured.
- **The 25 g whey + 5 g collagen study:** used muscle biopsies and a phenylalanine tracer. It increased muscle connective-protein FSR at rest versus water, but not significantly in the exercised leg; there was no whey-only comparator and no tendon biopsy.
- **Nulty 2025:** both groups received 50 mg vitamin C. The collagen group received 30 g hydrolyzed collagen, while control received energy-matched maltodextrin. Tendon CSA, stiffness and modulus improved more with collagen. Habitual diet was assessed at baseline but not tightly controlled throughout.
- **Daily collagen turnover:** 2-3 g/day is a commonly cited whole-body estimate from hydroxyproline metabolism. It is not a maximum, not tendon-only, and not net tissue gain.
- **The proline hypothesis:** proline is required but not a single switch. Glycine, lysine, all remaining sequence amino acids, vitamin C-dependent hydroxylation, cell signaling, energy and mechanical loading are also required. Human data do not establish a dietary proline saturation point.

### Bottom line

A well-fed person can synthesize collagen without eating collagen. Collagen powder is a concentrated way to deliver glycine, proline and hydroxyproline-containing peptides, but current evidence does not prove that these substrates are always the limiting step.

MEASUREMENT GLOSSARY

# Every abbreviation used in the report

The definitions below prevent a marker of a process from being mistaken for a finished tendon adaptation.

| Abbreviation | Full term | What it measures | What it cannot prove |
|---|---|---|---|
| **PINP / P1NP** | Procollagen type-I N-terminal propeptide | A propeptide cleaved when type-I procollagen is processed outside the cell. Serum concentration is an indirect systemic formation marker; widely used as a bone-formation marker. | Not tissue-specific; does not prove mature fibril deposition, retention or tendon function. |
| **β-CTX / CTX-I** | Beta-isomerized C-terminal telopeptide of type-I collagen | A circulating fragment associated with type-I collagen breakdown; clinically used mainly as a bone-resorption marker. | Not a tendon-specific breakdown measurement. |
| **FSR** | Fractional synthesis rate | Percentage of the measured protein pool synthesized per unit time, usually from stable-isotope incorporation into biopsy protein. | Gross synthesis, not net growth; depends on tissue and isolated protein fraction. |
| **MyoPS / MPS** | Myofibrillar / muscle protein synthesis | Rate of new contractile muscle-protein synthesis. | Not collagen or tendon synthesis. |
| **CSA** | Cross-sectional area | Anatomical size of a tendon or muscle, usually measured by ultrasound or MRI. | A larger tendon is not automatically healthier in tendinopathy. |
| **Stiffness** | Force divided by elongation | Mechanical resistance of the whole tendon to lengthening under load. | Depends on dimensions and material quality. |
| **Young's modulus** | Stress divided by strain | Intrinsic material-property estimate normalized for tendon dimensions. | Still model-dependent and measurement-sensitive. |
| **AUC / iAUC** | Area under the concentration-time curve | Total exposure over time; iAUC subtracts baseline. | Exposure is not utilization or tissue incorporation. |

### How PINP actually arises

Cells synthesize procollagen inside the cell. After secretion, N- and C-terminal propeptides are cleaved. PINP is the released N-terminal fragment. A serum rise therefore supports increased type-I procollagen formation/processing, but the concentration also depends on tissue source and clearance. It is a marker, not a required ingredient.

EVIDENCE LADDER

# From available substrate to a changed tendon

Higher levels are not always better-designed studies, but they answer the tendon question more directly.

| | | | |
|---|---|---|---|
| LEVEL 1 | **Blood amino acids**<br>Digestion and substrate availability | CAN SUPPORT<br>“The material reached the circulation.” | CANNOT SUPPORT<br>Cannot show synthesis or tissue destination. |
| LEVEL 2 | **Serum PINP / β-CTX**<br>Systemic type-I collagen formation/breakdown markers | CAN SUPPORT<br>“A systemic marker changed.” | CANNOT SUPPORT<br>Cannot localize the effect to tendon or count grams deposited. |
| LEVEL 3 | **Whole-body tracer flux**<br>Systemic collagen synthesis/breakdown with stable isotopes | CAN SUPPORT<br>“Whole-body collagen flux changed.” | CANNOT SUPPORT<br>Still does not identify tendon, skin, bone or muscle connective tissue. |
| LEVEL 4 | **Biopsy + tissue FSR**<br>Tracer incorporation into a defined tissue/protein fraction | CAN SUPPORT<br>“This sampled tissue synthesized more protein.” | CANNOT SUPPORT<br>Short-term gross synthesis; not necessarily mature tendon or net retention. |
| LEVEL 5 | **Long-term tendon structure and function**<br>CSA, stiffness, modulus, pain, function, injury outcomes | CAN SUPPORT<br>“The tendon or patient changed over time.” | CANNOT SUPPORT<br>Cannot by itself prove that substrate availability caused the mechanism. |

**Important terminology correction**

The Lee 2024 and Nulty 2024 dose-response papers describe PINP as a whole-body collagen-synthesis response. Because the actual outcome was serum PINP rather than a whole-body stable-isotope tracer, this report places them at Level 2.

STUDY MAP

# Levels 1-2: availability and systemic markers

These studies are valuable, but they do not directly measure collagen deposited in a tendon.

| Tier | Study | Intervention | Measured | Main result | Interpretation limit |
|---|---|---|---|---|---|
| **L1** | Aussieker 2024 | 30 g total: whey alone or whey + 5/10/15 g collagen | Plasma amino acids | 5 g collagen prevented the post-exercise glycine decline; 15 g gave the highest glycine iAUC. | Availability only - no synthesis endpoint. |
| **L2** | Shaw 2017 | 0/5/15 g vitamin-C-enriched gelatin before jump rope | Plasma amino acids, serum PINP, ex-vivo engineered ligament response | 15 g produced the strongest PINP signal and serum supported greater ex-vivo collagen production. | Small acute study; serum marker and lab tissue, not human tendon deposition. |
| **L2** | Lis & Baar 2019 | 15 g gelatin, hydrolyzed collagen, gummy or placebo + vitamin C | Plasma amino acids and serum PINP | Gelatin/HC increased collagen amino acids; PINP response was variable; gummy did not reproduce the same signal. | Ten men; marker variability; no tendon biopsy. |
| **L2** | Lee 2024 | 0/15/30 g HC + 50 mg vitamin C, 1 h before high-intensity squats | Serum PINP, β-CTX and amino acids | PINP AUC: 30 g > 15 g and 0 g; 15 g was not significantly different from 0 g. | Not a tracer measurement despite “whole-body synthesis” wording. |
| **L2** | Nulty 2024 | 0/15/30 g vitamin-C-enriched HC before leg press | Serum PINP, β-CTX and amino acids | Dose-response in middle-aged trained men; 30 g > 15 g > 0 g for PINP response. | Eight men; systemic marker; no tendon-specific synthesis. |
| **Not public** | NCT05427279 | 20 g HC vs 20 g whey isolate vs PrimaColl vs maltodextrin; all + 50 mg C | Planned PINP and ex-vivo model | The direct whey+C vs collagen+C trial is completed, but public numeric results were not located. | Cannot be used as evidence until results are public. |

*Primary sources: Shaw 2017; Lis & Baar 2019; Lee 2024; Nulty 2024; Aussieker 2024; ClinicalTrials.gov NCT05427279.*

EVIDENCE RESULTS

# Level 4 studies: direct tissue synthesis measurements

These studies used stable isotopes and biopsies. The decisive question is which tissue was sampled: tendon, intramuscular connective tissue, muscle, or skin.

| Study / design | Participants + intervention | Direct method | What was found | What the result means |
|---|---|---|---|---|
| **Miller et al. 2005<br>Direct patellar-tendon FSR** | Two cohorts of healthy young men (n=8 and n=6); 1 h one-legged kicking at 67% Wmax. No supplement comparison. | IV stable isotopes plus patellar-tendon and quadriceps biopsies over 72 h; serum and local microdialysate PINP were also measured. | Tendon-collagen and muscle-connective synthesis rose rapidly, peaked around 24 h and remained above rest at 72 h. Serum/local PINP did not rise despite the biopsy FSR response. | Direct proof that loading raises tendon synthesis. It also shows why unchanged blood PINP does not exclude a tissue-level synthesis response. |
| **Aussieker et al. 2023<br>Whey vs collagen vs placebo** | 45 recreational athletes (30 men, 15 women), 15/group. After exercise: 30 g whey, 30 g collagen, or non-caloric placebo. | L-[ring-13C6]-phenylalanine infusion and muscle biopsies over 5 h; myofibrillar and intramuscular connective fractions. | Myofibrillar FSR (%/h): whey 0.041, collagen 0.036, placebo 0.032; only whey > placebo. Connective FSR: 0.072, 0.068, 0.058; overall P=0.09, not significant. | Whey supported muscle synthesis. Neither protein significantly raised early intramuscular connective FSR. This was not a tendon biopsy. |
| **Aussieker et al. 2025<br>25 g whey + 5 g collagen** | 28 recreationally active men, 14/group; unilateral exercise. Blend versus non-caloric placebo. No whey-only arm. | Phenylalanine tracer + muscle biopsies over 5 h; rested and exercised legs; myofibrillar and connective fractions. | Connective FSR: rested 0.062 vs 0.051%/h (P<0.05); exercised 0.090 vs 0.079%/h (P=0.11). Myofibrillar FSR was higher with blend both rested and exercised. | The blend increased intramuscular connective synthesis at rest, not significantly after exercise. It cannot isolate the effect of the 5 g collagen or prove a tendon effect. |
| **Aussieker et al. 2025<br>Collagen vs matched free AAs** | 45 young adults (21 men, 24 women): 30 g hydrolyzed collagen, 30 g free AAs matched to its profile, or placebo. | Stable-isotope infusion; muscle and skin biopsies over 6 h; unilateral exercise. | Connective FSR (%/h), rested: placebo 0.065, collagen 0.063, AAs 0.061; exercised: 0.098, 0.092, 0.085. No group differences. Skin synthesis also did not differ. | Large rises in glycine/proline did not increase synthesis in these tissues/time window. Substrate availability was not the limiting step here; tendon was not sampled. |

### Level 4 does not automatically mean “tendon evidence”

Miller directly sampled patellar tendon. The three nutrition studies sampled skeletal-muscle connective fractions and/or skin. They are methodologically strong synthesis studies, but their tissue destination must remain explicit.

*Miller et al. J Physiol. 2005;567:1021-1033. DOI 10.1113/jphysiol.2005.093690; Aussieker et al. Med Sci Sports Exerc. 2023/2025. DOIs 10.1249/MSS.0000000000003214, 10.1249/MSS.0000000000003596, and the 2025 collagen-vs-free-AA biopsy study.*

EVIDENCE RESULTS

# Level 5 overview: randomized trials that measured the tendon

This is the clinically closest evidence tier. Positive and null trials are shown together before the detailed result tables.

| Study | Population / duration | Comparison | Tendon outcomes | Headline result |
|---|---|---|---|---|
| **Nulty 2025** | Middle-aged men; 12 wk, 2 RT sessions/wk | 30 g HC vs carbohydrate; both +50 mg C | Patellar CSA, stiffness, modulus | Positive for all three tendon outcomes. |
| **Lee 2023 academy soccer** | Female academy players; 10 wk, 3 sessions/wk | 30 g HC vs energy-matched carbohydrate; both +500 mg C | Patellar stiffness, modulus, CSA | Positive stiffness/modulus; no CSA difference. |
| **Lee 2024 professional soccer** | Professional female players; 10 wk preseason | 30 g HC vs energy-matched carbohydrate; both +500 mg C | Patellar stiffness, modulus, CSA | Positive stiffness/modulus; no collagen-specific CSA effect. |
| **Jerger 2022 Achilles** | Young men; 14 wk high-load RT | 5 g specific peptides vs 5 g placebo; no added C | Achilles CSA and stiffness | Positive CSA; no between-group stiffness effect. |
| **Jerger 2023 patellar** | 50 moderately active men; 14 wk high-load RT | 5 g specific peptides vs placebo; no added C | Regional patellar CSA and stiffness | Positive CSA at 60-70% tendon length; no mechanical superiority. |
| **Balshaw 2023** | 39 young men; 15 wk RT | 15 g peptides vs maltodextrin; no added C | Patellar/aponeurosis size and mechanics | Null between-group tendon result. |
| **Nulty & Erskine 2025** | 22 elite female Master hockey athletes; 8 wk | 30 g HC vs carbohydrate before RT; vitamin C in both, but not perfectly matched | Patellar CSA; pRFD; no stiffness measure | Positive CSA and pRFD; stiffness not measured. |

### Why results differ

Dose is not the only variable. Studies differ in tendon, participant age/sex/training status, loading program, supplement timing, vitamin C, protein intake, product-specific peptides, imaging location and statistical power. A single universal “optimal dose” cannot be inferred.

EVIDENCE RESULTS

# Level 5 detailed results I: 30 g trials with matched vitamin C

The dietary-protein column is essential because most placebo groups received carbohydrate rather than an equal amount of non-collagen protein.

| Study / protocol | Participants + randomized comparison | Dietary protein control | Exact tendon result | Interpretation |
|---|---|---|---|---|
| **Nulty 2025**<br>**Patellar tendon** | 20 middle-aged recreationally active men; COL n=9, PLA n=11; 12 wk supervised lower-limb RT, 2x/wk. Post-training: 30 g HC vs 30.5 g maltodextrin. Both received 50 mg vitamin C. | Habitual protein: COL 81.6+/-22.7 g/d, about 1.05 g/kg/d; PLA 92.6+/-19.1 g/d, about 1.10 g/kg/d. Three-day diary at baseline; not controlled feeding. COL added 60 g protein/week (about 8.6 g/d averaged over the week). | Change: mean patellar CSA +6.8 vs +1.2 mm2; stiffness +661 vs +247 N/mm; Young's modulus +0.21 vs +0.09 GPa. No extra muscle thickness, strength or power benefit. | Strong positive tendon result with vitamin C and training matched. However, collagen also added protein/nitrogen only to COL, and diet was not monitored as controlled feeding throughout. |
| **Lee et al. 2023**<br>**Academy female soccer** | 17 players, age 17+/-0.9; COL n=8, PLA n=9; 10 wk in-season strength/plyometric/pitch training, 3x/wk. Post-session: 30 g HC vs energy-matched carbohydrate. Both +500 mg vitamin C. | Diet data available for 14: habitual protein COL 1.2+/-0.1 vs PLA 1.4+/-0.3 g/kg/d. Including supplement: COL 1.4+/-0.1 vs PLA 1.4+/-0.3 g/kg/d. Three-day diary; not controlled feeding. | Stiffness +18.0+/-12.2% vs +5.1+/-10.4% (P=0.049); Young's modulus +17.3+/-11.9% vs +4.8+/-10.3% (P=0.035). No between-group difference in CSA, strength or VL thickness. | Positive mechanical/material outcomes. Small athletic sample; mixed soccer and gym loading; incomplete dietary records, but relative total protein was similar. |
| **Lee et al. 2024**<br>**Professional female soccer** | 11 professional players; COL n=6, PLA n=5; 10 wk preseason high-intensity RT/plyometric/pitch training, 3x/wk. Pre-training: 30 g HC vs energy-matched carbohydrate. Both +500 mg vitamin C. | Diet data n=10: habitual protein COL 1.6+/-0.5 vs PLA 1.3+/-0.3 g/kg/d; including supplement COL 1.8+/-0.5 vs PLA 1.3+/-0.3. Differences were not statistically significant, but the sample was very small; not controlled feeding. | Stiffness +15.4+/-3.1% vs +4.6+/-3.0% (P=0.002); Young's modulus +14.2+/-4.0% vs +3.4+/-2.8% (P=0.004). CSA increased over time, but no group interaction (P=0.934). | Replicates a mechanical advantage in elite women. Very small sample and COL had greater numerical protein intake; no collagen-specific tendon hypertrophy. |

### What matched vitamin C tells us

Because both arms received the same vitamin C in these three trials, a vitamin C difference cannot explain the group effect. The comparison is still collagen protein versus carbohydrate, not collagen versus an equal dose of whey, soy or matched free amino acids.

EVIDENCE RESULTS

# Level 5 detailed results II: lower-dose, null and newer athlete trials

These studies prevent the evidence summary from becoming a selection of only positive 30 g findings.

| Study / protocol | Participants + randomized comparison | Dietary protein / vitamin C control | Exact tendon result | Interpretation |
|---|---|---|---|---|
| **Jerger et al. 2022 Achilles** | 40 healthy young men; 14 wk high-load RT. Daily 5 g specific collagen peptides vs 5 g placebo. No added vitamin C. | Habitual intake was not controlled feeding. Group-mean estimate: peptide group about 87.1 g/d / 77.9 kg = 1.12 g/kg/d; placebo about 93.6 g/d / 76.4 kg = 1.23 g/kg/d. | Achilles CSA +11.0% vs +4.7% (P=0.002). Muscle thickness +7.3% vs +2.7% (P=0.014). Stiffness and strength rose in both groups with no between-group difference. | Positive hypertrophy, null mechanical superiority. Product-specific 5 g peptides; industry funded; no vitamin C protocol. |
| **Jerger et al. 2023 Patellar** | 50 healthy moderately active men; 14 wk knee-extensor RT, 3x/wk at 70-85% 1RM. Daily 5 g specific peptides vs placebo. No added vitamin C. | Dietary protein values were not reported in the accessible primary report; diet was not a controlled feeding comparison. | MRI: greater patellar CSA increase with peptides at 60% and 70% of tendon length from the proximal insertion. Tendon stiffness, muscle CSA and maximal strength improved similarly between groups. | Positive regional morphology, not a global mechanical advantage. Demonstrates that measurement location changes the apparent result. |
| **Balshaw et al. 2023 Patellar + aponeurosis** | 39 young men; 15 wk lower-body RT, 3x/wk. Daily 15 g specific peptides vs 15 g maltodextrin. No added vitamin C. | Habitual protein CP 1.64+/-0.53 vs PLA 1.44+/-0.56 g/kg/d. Including supplement: CP 1.85+/-0.54 vs PLA 1.44+/-0.56 (P=0.027). Diet assessed during study, not controlled feeding. | No group-by-time difference for any tendon adaptation (P=0.365-0.877). PT stiffness +17.3% CP vs +20.9% PLA; modulus +17.8% vs +20.6%; mean PT CSA +1.1% vs +1.7%. | Important null trial. Training clearly adapted tendon, but 15 g peptides did not add benefit despite higher total protein in CP. |
| **Nulty & Erskine 2025 Female Master hockey** | 22 international premenopausal Master athletes; 8 wk eccentric RT, 3x/wk. 30 min pre-RT: 30 g HC vs carbohydrate. Both took 500 mg C, but HC powder also contained 120 mg C (about 620 vs 500 mg). | Participants maintained habitual diet and avoided whey/creatine; quantitative protein intake was not reported. Thus, diet balance cannot be checked. | PT CSA increased about +5% COL vs +2% PLA (interaction P=0.014 in the published analysis); pRFD +27.3+/-19.2% vs +8.0+/-19.6% (interaction P=0.039). MVF/VL thickness similar; stiffness not measured. | Positive size/performance trial, but vitamin C was not perfectly matched, dietary protein was unreported, and increased CSA must not be translated into measured stiffness. |

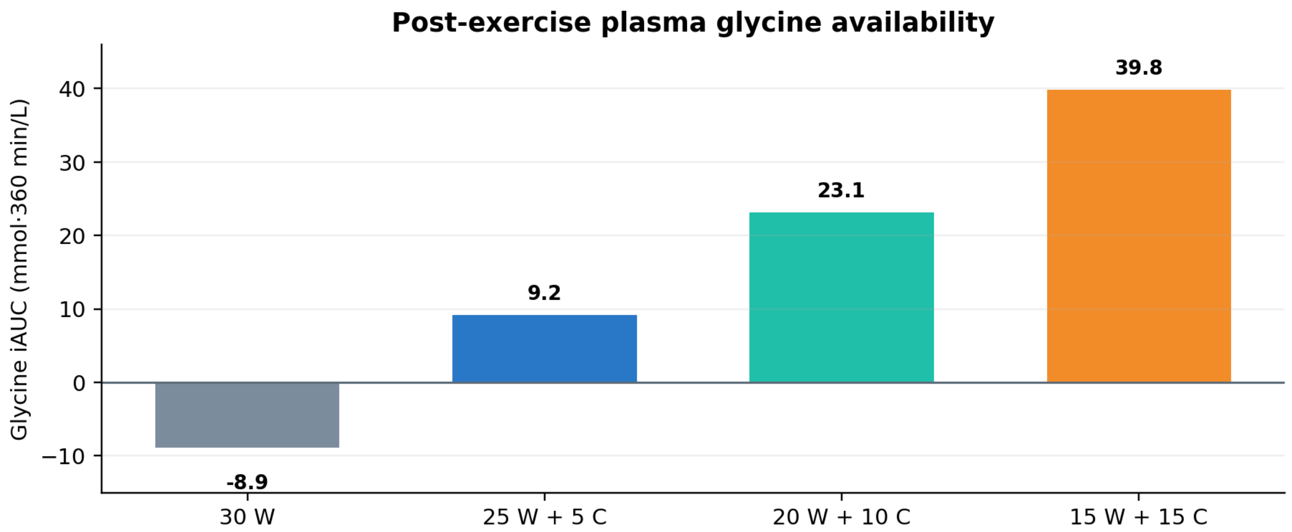
### The direct-outcome pattern

The long-term record is mixed rather than uniformly positive: several trials report greater tendon size or mechanics with collagen, while Balshaw found no additive tendon effect. Positive studies also differ in whether size, stiffness or modulus changed.

DETAILED STUDY

# The 30 g blend experiment did not measure synthesis

The purpose was to find how much collagen had to replace whey to prevent low post-exercise glycine availability.




| Drink (30 g total protein) | What increased most | What decreased as collagen replaced whey | What can be concluded |
|---|---|---|---|
| **30 g whey** | Leucine and essential amino acids | Glycine fell below baseline after exercise | Best complete-protein profile; no synthesis measurement. |
| **25 g whey + 5 g collagen** | Glycine no longer fell; robust leucine/EAA rise remained | Slightly less whey/EAA than whey alone | Five grams was enough to correct plasma glycine availability. |
| **20 g whey + 10 g collagen** | Higher glycine and proline exposure | Less leucine/EAA | More collagen-type amino acids, but no evidence of more collagen synthesis. |
| **15 g whey + 15 g collagen** | Highest glycine exposure | Largest loss of whey/EAA | Highest glycine does not equal the best tendon outcome. |

### Correct answer to “which blend produced the most collagen?”

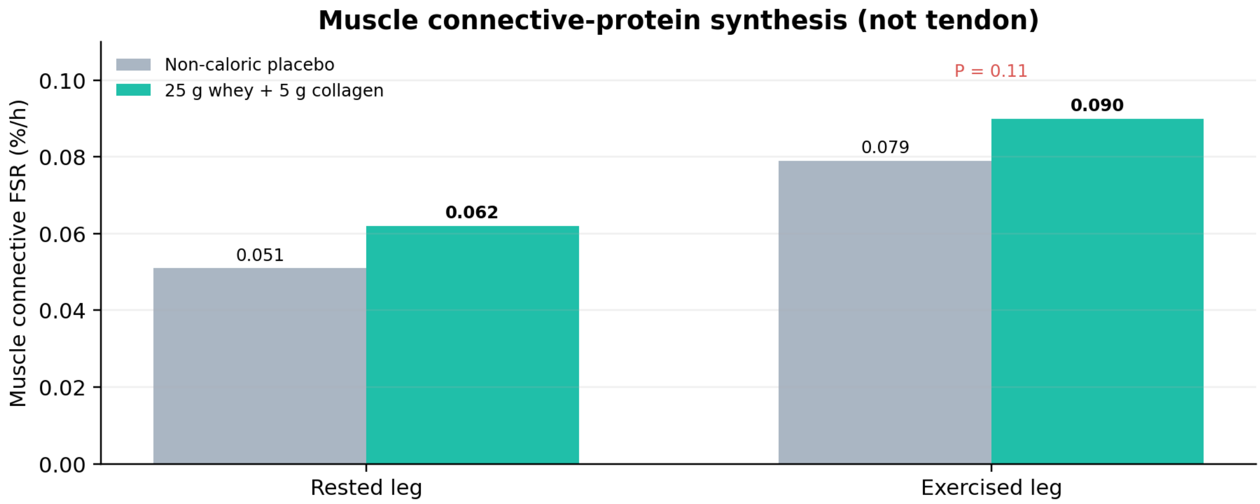
The study cannot answer that question. The 15+15 drink produced the highest plasma glycine exposure. The 25+5 drink was selected as a practical amino-acid compromise for the next biopsy study.

*Aussieker et al. Coingestion of Collagen With Whey Protein Prevents Postexercise Decline in Plasma Glycine Availability. Int J Sport Nutr Exerc Metab. 2024;34:189-198. DOI: 10.1123/ijsnem.2023-0264.*

DETAILED STUDY

# 25 g whey + 5 g collagen: what the biopsy study really found

This is stronger than a blood-amino-acid study, but it sampled intramuscular connective protein rather than tendon and did not include a whey-only comparator.




| Protein fraction / leg | 25+5 blend | Placebo | P value | Interpretation |
|---|---|---|---|---|
| **Myofibrillar FSR - rested** | 0.038+/-0.008%/h | 0.031+/-0.006%/h | <0.05 | Blend increased muscle-contractile synthesis. |
| **Myofibrillar FSR - exercised** | 0.052+/-0.011%/h | 0.039+/-0.009%/h | <0.01 | Blend added to the exercise response. |
| **Muscle-connective FSR - rested** | 0.062+/-0.013%/h | 0.051+/-0.010%/h | <0.05 | Statistically higher with blend at rest. |
| **Muscle-connective FSR - exercised** | 0.090+/-0.021%/h | 0.079+/-0.016%/h | 0.11 | Not statistically different after exercise. |

### Design and method

28 recreationally active young men, randomized double-blind; n=14 blend and n=14 non-caloric placebo. One leg exercised, one rested. Continuous L-[ring-13C6]-phenylalanine infusion with repeated blood sampling and muscle biopsies for 5 h.

### Nutrition context

No whey-only group. Vitamin C was not randomized in the drink. Reported habitual vitamin C over the preceding two days was about 141+/-63 mg/d in blend and 163+/-85 mg/d in placebo, suggesting adequate status in both.

### Correct conclusion

The tested blend increased intramuscular connective-protein FSR at rest versus water, but did not significantly increase it in the exercised leg. The experiment cannot show that 5 g collagen was responsible, that it is an optimal dose, or that a tendon synthesized more collagen than after whey alone.

*Aussieker et al. Med Sci Sports Exerc. 2025;57:544-556. DOI: 10.1249/MSS.0000000000003596. Trial NCT05386771.*

DETAILED STUDIES

# Raising glycine and proline does not guarantee a higher tissue FSR

Two biopsy experiments challenge the simple "more collagen amino acids = more connective synthesis" equation.

| Study | Groups | Tissue / method | Result | Meaning |
|---|---|---|---|---|
| **Whey vs collagen vs placebo (2023)** | 30 g whey; 30 g collagen; non-caloric placebo | Stable-isotope infusion + skeletal-muscle biopsies | Whey increased myofibrillar FSR. Muscle connective FSR: 0.072, 0.068 and 0.058%/h; overall group difference was not significant (P=0.09). | Neither protein further increased early post-exercise intramuscular connective FSR. |
| **Collagen vs matched free AAs (2025)** | 30 g hydrolyzed collagen; 30 g free AAs matching its profile; placebo | Stable-isotope infusion + muscle and skin biopsies | Both active drinks strongly increased circulating glycine/proline, but neither further increased muscle connective or skin-protein FSR. | Systemic substrate availability was not limiting in these sampled tissues and time window. |

### Do these studies disprove collagen for tendons?

No. They studied intramuscular connective tissue and/or skin, not tendon. They do show that high amino-acid concentrations alone are insufficient to guarantee a measurable synthesis response in every connective-tissue fraction.

### Substrate-limited model

If glycine/proline are scarce, additional collagen could increase synthesis. The plasma-glycine study supports the possibility of scarcity after whey/exercise.

### Capacity-limited model

If cells, translation, enzyme activity, matrix assembly or mechanical signaling are limiting, more substrate will be oxidized or used elsewhere rather than converted proportionally into collagen.

*Aussieker et al. Med Sci Sports Exerc. 2023. DOI: 10.1249/MSS.0000000000003214; Aussieker et al. Med Sci Sports Exerc. 2025;57:2394-2408.*

ACUTE EVIDENCE

# PINP dose-response: useful signal, limited localization

The acute studies support a systemic formation response, not a measured number of grams in a tendon.

| Study | Protocol | PINP result | Additional measurement | Evidence statement |
|---|---|---|---|---|
| **Shaw 2017** | 0, 5 or 15 g gelatin + vitamin C; 1 h before 6 min jump rope | 15 g produced the strongest post-exercise PINP signal | Blood AAs; participant serum applied to engineered ligaments | Mechanistic support for timing/substrate; not a human tendon outcome. |
| **Lis & Baar 2019** | 15 g gelatin, HC, mixed gummy or placebo; all vitamin-C enriched | Gelatin and HC showed variable ~20% trends; gummy did not reproduce signal | Amino acids in subset | Product form and exposure matter; very small study. |
| **Lee 2024** | 0, 15 or 30 g HC + 50 mg C; 1 h before squats | PINP AUC: 267 vs 235 vs 219 μg·L−1·h; 30 g > 15 and 0 | Amino acids; β-CTX | Supports a 30 g systemic marker response. 15 g was not different from 0 g. |
| **Nulty 2024** | 0, 15 or 30 g HC + 50 mg C before leg press | 30 g > 15 g > 0 g in eight middle-aged men | Amino acids; β-CTX | Suggests dose response in this population; no tissue localization. |

### PINP interpretation in one sentence

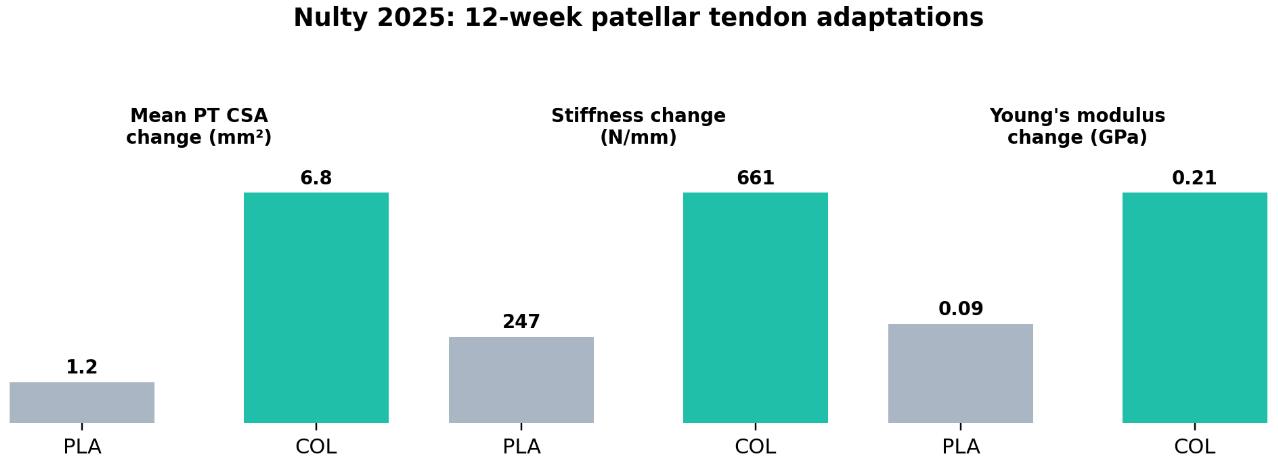
A rise means more type-I procollagen was formed/processed somewhere in the body, but it does not tell us how much became mature tendon collagen, whether it was retained, or whether the signal came mainly from tendon rather than bone or another tissue.

*Lee et al. J Nutr. 2024;154:2076-2086. DOI: 10.1016/j.tjnut.2023.10.030; Nulty et al. AJP Endocrinol Metab. 2024;327:E668-E677. DOI: 10.1152/ajpendo.00252.2024.*

BEST DIRECT TENDON TRIAL DISCUSSED

# Nulty 2025: both groups received vitamin C

The difference was 30 g hydrolyzed collagen versus an energy-matched carbohydrate placebo, added to the same supervised training program.




| Feature | Collagen group | Placebo group | Why it matters |
|---|---|---|---|
| **Participants** | n=9; middle-aged recreationally active men | n=11; matched middle-aged men | Small parallel trial; lower-limb resistance-training naive. |
| **Training** | Progressive supervised lower-limb resistance training twice weekly for 12 weeks | Same | The mechanical stimulus was matched. |
| **Post-training drink** | 30 g hydrolyzed collagen + 50 mg vitamin C | 30.5 g maltodextrin + 50 mg vitamin C | Yes - both groups received identical vitamin C. Calories were approximately matched, protein was not. |
| **Habitual protein** | 81.6 +/- 22.7 g/day; about 1.05 g/kg/day from group means (reported approximately 1.1) | 92.6 +/- 19.1 g/day; about 1.10 g/kg/day from group means | No significant baseline difference. Three-day diary at baseline; this was not controlled feeding. |
| **During intervention** | 30 g protein after each of 2 weekly sessions = 60 g/week, equivalent to about +8.6 g/day or +0.11 g/kg/day when averaged across the week | 0 g supplemental protein; carbohydrate placebo only | The intervention changed collagen peptides, total protein/nitrogen and amino-acid profile together. |
| **Tendon result** | Greater gains in mean CSA, stiffness and Young's modulus | Smaller gains; CSA change minimal | This is a true long-term tendon outcome, much stronger than PINP. |
| **Muscle result** | No extra benefit for muscle thickness, strength or power | Training improved these outcomes similarly | Collagen did not behave like a high-quality muscle protein. |

### Fair conclusion

Under this exact protocol, adding 30 g hydrolyzed collagen after twice-weekly training improved measured patellar-tendon adaptation more than training plus vitamin C and carbohydrate. Because habitual diet was only assessed at baseline and the intervention added protein only to COL, the study cannot isolate a unique peptide effect from all consequences of adding 30 g collagen protein.

*Nulty CD, Phelan K, Erskine RM. Eur J Sport Sci. 2025;25:e12281. DOI: 10.1002/ejsc.12281. Trial NCT06402890.*

LONG-TERM CONTEXT

# The positive Nulty result is not isolated - but protocols vary

Dose, training intensity, timing, participant age and habitual tendon loading all differ across trials.

| Trial / context | Collagen protocol | Matched factors | Tendon outcome | Main caution |
|---|---|---|---|---|
| **Female soccer players, 10 weeks** | 30 g collagen hydrolysate after training, 3 days/week | Energy-matched placebo; both groups 500 mg vitamin C | Greater increases in stiffness and Young's modulus; no CSA difference | High-level athletes; mixed soccer/strength/plyometric loading. |
| **Middle-aged men, 12 weeks (Nulty)** | 30 g HC after training, 2 days/week | Energy-matched placebo; both groups 50 mg vitamin C | Greater CSA, stiffness and modulus | Small sample; extra protein only in COL. |
| **Specific collagen peptides, ~5 g/day** | Daily lower dose with resistance training | Placebo-controlled | Some CSA changes, inconsistent mechanical superiority | Product-specific peptides; lower dose; different tendons. |
| **15 g/day resistance-training trials** | 15 g collagen with structured training | Placebo-controlled | Mixed or null additive tendon-mechanical effects | A lower dose may be insufficient, or other protocol factors may dominate. |
| **2026 systematic review** | Eight randomized tendon trials | Study-level synthesis | Higher-dose 15-30 g trials tended to show stronger CSA/stiffness outcomes | The review rated evidence positively, but samples and protocols remain heterogeneous. |

### Timing is not settled

The classic acute studies dosed collagen 30-60 minutes before loading to align amino-acid availability with the stimulus. Several positive chronic trials dosed immediately after training. Current evidence supports pairing collagen with loading more strongly than it supports one universal timing rule.

*Lee et al. Front Physiol. 2023;14:1089971. DOI: 10.3389/fphys.2023.1089971; Buchalski et al. J Funct Morphol Kinesiol. 2026;11:130. DOI: 10.3390/jfmk11010130.*

PHYSIOLOGY

# What happens after collagen is swallowed

The supplement is not transported intact from the stomach into a tendon.

| | |
|---|---|
| **1. Gastric and intestinal digestion** | Hydrolyzed collagen is already fragmented, but digestive enzymes further produce free amino acids and small peptides. |
| **2. Absorption** | Glycine, proline, alanine and other amino acids enter portal blood. Some hydroxyproline-containing di- and tripeptides, such as Pro-Hyp, can transiently appear in plasma. |
| **3. Common metabolic pool** | Most absorbed nitrogen enters the same systemic amino-acid economy as amino acids from meat, whey, soy or pea. Tissues compete for use. |
| **4. Possible peptide signaling** | Collagen-derived peptides may affect fibroblast/tenocyte signaling in experimental models. Their importance for human tendon adaptation remains plausible but not fully quantified. |
| **5. Oxidation and alternative use** | Amino acids not used for protein synthesis can be converted into other metabolites, oxidized for energy, or have nitrogen excreted as urea. |

### Hydroxyproline detail

Dietary hydroxyproline is not directly encoded into a new collagen chain. Ribosomes insert proline; specific proline residues are then hydroxylated after translation. Dietary hydroxyproline can be metabolized and collagen-derived peptides may signal, but it is not simply “plugged” into the new helix.

PHYSIOLOGY

# Collagen synthesis requires more than proline + vitamin C

Proline is necessary, but it is neither the only building block nor a stand-alone trigger.

| | | |
|---|---|---|
| 1 | **Mechanical / biological signal** | Tenocyte or fibroblast signaling, transcription and translation determine production capacity. |
| 2 | **Proteinogenic amino acids** | Glycine occurs every third residue; proline is abundant; lysine is essential; many other amino acids complete the sequence. |
| 3 | **Intracellular processing** | Three pro-alpha chains are translated; selected proline and lysine residues are hydroxylated. |
| 4 | **Vitamin C-dependent enzymes** | Ascorbate maintains iron in prolyl and lysyl hydroxylases, supporting helix stability and secretion. |
| 5 | **Extracellular maturation** | Propeptides including PINP are cleaved; molecules assemble into fibrils and fibers. |
| 6 | **Cross-linking and retention** | Lysyl oxidase, matrix organization, degradation rate and loading history determine final mechanical quality and net gain. |

### Potential nutritional bottlenecks

Low total protein, low lysine, low vitamin C, inadequate energy, severe micronutrient deficiency or low availability of glycine/proline could constrain production.

### Potential non-nutritional bottlenecks

Cell number/activity, age, hormones, blood supply, mRNA translation, matrix assembly, cross-linking, degradation and the magnitude/timing of loading can dominate.

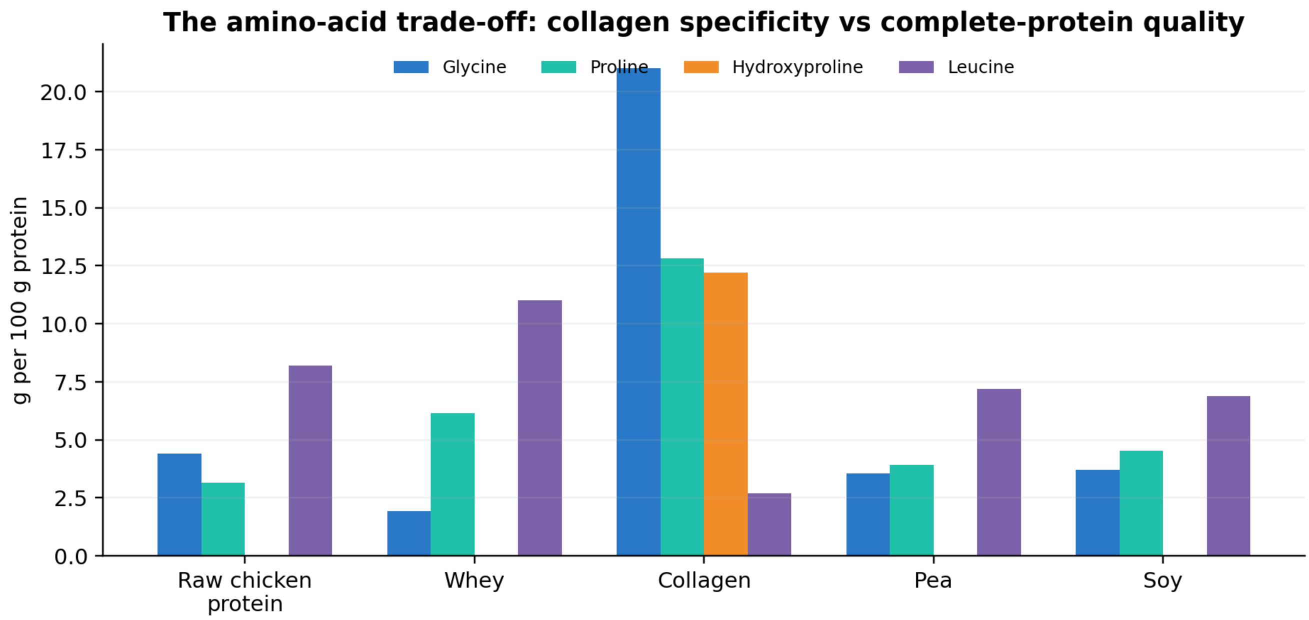
### No established “proline ceiling”

No human dose-response study has titrated isolated proline plus vitamin C and directly measured tendon-collagen incorporation to identify a maximum usable dose. The upper limit is therefore unknown.

FOOD COMPOSITION

# The unique feature of collagen is concentration, not exclusive amino acids

Other proteins contain glycine and proline; collagen supplies much more glycine, proline and hydroxyproline but much less leucine and fewer essential amino acids.




| Protein source | Glycine | Proline | Hydroxyproline | Leucine | Lysine | Interpretation |
|---|---|---|---|---|---|---|
| **Raw chicken breast protein** | 4.39 | 3.15 | ~0* | 8.20 | 9.53 | Complete protein; modest gly/pro. Values normalized to protein. |
| **Whey protein** | 1.92 | 6.14 | 0 | 11.01 | 9.09 | Best leucine/EAA profile; glycine is low. |
| **Collagen/gelatin** | 21.0 | 12.8 | 12.2 | 2.70 | 3.50 | Concentrated collagen-type AAs; incomplete for muscle. |
| **Pea isolate** | 3.54 | 3.92 | 0 | 7.20 | 5.94 | Plant complete-ish profile with lower methionine. |
| **Soy isolate** | 3.71 | 4.54 | 0 | 6.88 | 4.67 | Good plant profile; less gly/pro than collagen. |

### Raw chicken - the food amount people actually eat

Approximately 100 g raw, skinless chicken breast provides about 22-23 g protein, ~1.0 g glycine, ~0.7 g proline, ~1.85 g leucine and ~2.1 g lysine. Cooking changes water weight and values per 100 g cooked food, which is why this report uses raw food for the practical calculation.

*Values are approximate and vary by raw material and analytical method. *Pure skeletal muscle has little hydroxyproline; raw breast can contain small variable amounts from connective tissue. Sources: USDA FoodData Central and analytical protein-source studies; collagen profile based on hydrolyzed collagen used in human trials.*

FOOD COMPOSITION

# Full amino-acid profile - grams per 100 g protein

Normalization to protein makes the sources comparable; it is different from grams per 100 g food.

| Amino acid | Raw chicken breast | Whey | Collagen | Pea isolate | Soy isolate |
|---|---|---|---|---|---|
| **Glycine** | 4.39 | 1.92 | 21.00 | 3.54 | 3.71 |
| **Proline** | 3.15 | 6.14 | 12.80 | 3.92 | 4.54 |
| **Hydroxyproline** | 0.00 | 0.00 | 12.20 | 0.00 | 0.00 |
| **Alanine** | 5.79 | 5.38 | 8.90 | 4.04 | 3.85 |
| **Arginine** | 6.70 | 2.18 | 7.30 | 7.45 | 6.60 |
| **Glutamic acid** | 14.68 | 19.84 | 10.30 | 16.29 | 17.05 |
| **Aspartic acid** | 9.32 | 10.50 | 6.00 | 10.80 | 10.50 |
| **Serine** | 3.78 | 5.12 | 3.10 | 4.55 | 4.67 |
| **Lysine** | 9.53 | 9.09 | 3.50 | 5.94 | 4.67 |
| **Leucine** | 8.20 | 11.01 | 2.70 | 7.20 | 6.88 |
| **Isoleucine** | 4.86 | 4.86 | 1.50 | 2.91 | 2.61 |
| **Valine** | 5.13 | 4.48 | 2.40 | 3.41 | 3.03 |
| **Threonine** | 4.45 | 6.91 | 1.90 | 3.16 | 3.16 |
| **Phenylalanine** | 4.00 | 3.20 | 2.10 | 4.67 | 4.40 |
| **Methionine** | 2.58 | 2.30 | 0.90 | 0.38 | 0.41 |
| **Histidine** | 3.69 | 1.79 | 1.10 | 2.02 | 2.06 |
| **Tyrosine** | 3.57 | 3.07 | 1.00 | 3.28 | 3.03 |
| **Tryptophan** | 1.25 | 1.50 | 0.00 | 0.95 | 1.05 |
| **Cysteine** | 1.04 | 1.02 | 0.00 | 0.25 | 0.28 |

*Approximate reference profiles. Hydroxyproline and hydroxylysine are distinctive post-translational collagen residues; ordinary isolates contain essentially none. Exact commercial powders vary by manufacturer.*

TURNOVER + FOOD CALCULATION

# What does “2-3 g of collagen per day” actually mean?

The estimate is a whole-body gross turnover value inferred from hydroxyproline metabolism - not maximum production and not tendon growth.

| 2-3 g/day | All tissues | Gross flux |
|---|---|---|
| Common whole-body collagen turnover estimate | Skin, bone, vessel, muscle ECM, tendon, ligament, organs | Synthesis and breakdown can be similar, giving zero net gain |

| If 2-3 g new collagen is synthesized | 2 g collagen | 3 g collagen | Calculation |
|---|---|---|---|
| **Glycine in finished collagen** | 0.42 g | 0.63 g | 2 or 3 g × 21.0% |
| **Proline remaining as proline** | 0.26 g | 0.38 g | 2 or 3 g × 12.8% |
| **Proline precursor for hydroxyproline** | 0.21 g | 0.32 g | Hyp mass × 115.13/131.13 |
| **Total proline precursor** | 0.47 g | 0.71 g | Proline + proline-equivalent used for Hyp |
| **Lysine precursor incl. hydroxylysine** | ~0.10 g | ~0.15 g | Lysine + molecular-weight-adjusted hydroxylysine |
| **All other amino acids combined** | ~1.01 g | ~1.52 g | Remaining mass of the collagen sequence |

### The calculation is a stoichiometric floor, not a dietary requirement

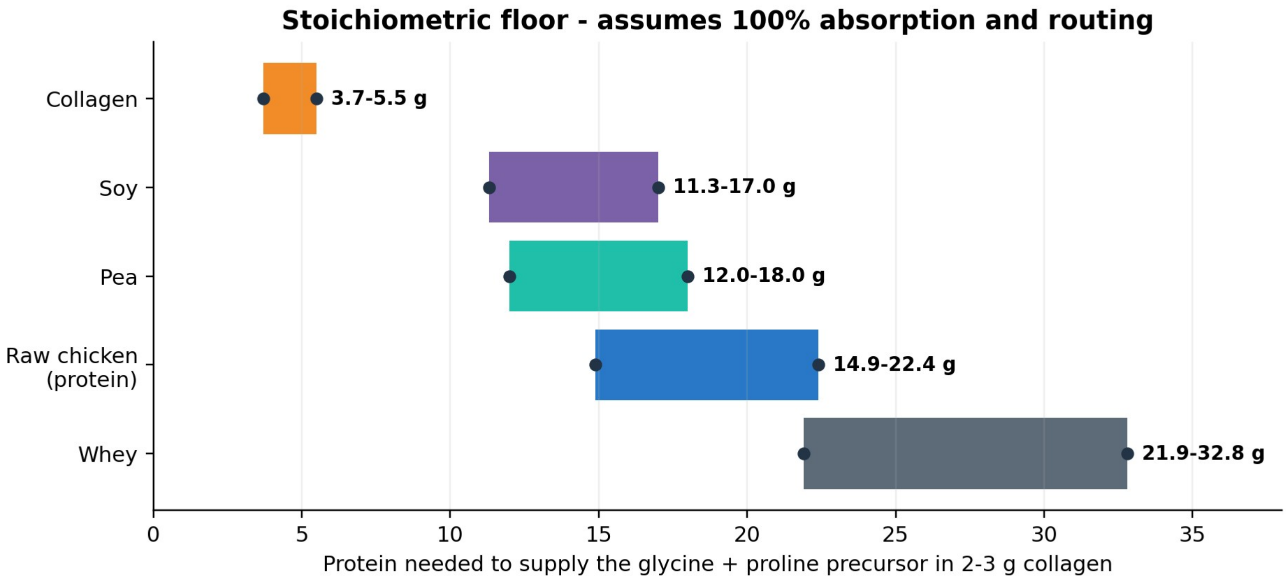
The body recycles amino acids from protein breakdown and synthesizes glycine and proline endogenously, which lowers the external requirement. Conversely, not every absorbed gram is routed to collagen, which raises the food intake needed if diet alone had to supply the entire flux.

*The 2-3 g/day estimate is cited in human hydroxyproline-metabolism literature. Collagen composition uses an illustrative hydrolyzed collagen profile. Molecular-weight correction accounts for the oxygen added during proline hydroxylation.*

TURNOVER + FOOD CALCULATION

# How much protein supplies the theoretical glycine + proline floor?

This model asks a narrow question: how much of each protein contains at least the glycine and proline precursor present in 2-3 g of new collagen?




| Source | Pure protein required | Approximate food / powder amount | Limiting amino acid in model | Interpretation |
|---|---|---|---|---|
| **Collagen protein** | 3.7-5.5 g | ~4-6 g collagen powder | Proline (dietary hydroxyproline is not counted as directly incorporable) | Most concentrated substrate source. |
| **Soy isolate** | 11.3-17.0 g | ~13-19 g 90% isolate | Glycine | Can theoretically supply the mass floor without dietary collagen. |
| **Pea isolate** | 12.0-18.0 g | ~14-21 g 85% isolate | Proline, narrowly | Can theoretically supply the mass floor. |
| **Raw chicken breast protein** | 14.9-22.4 g | ~65-100 g raw breast at 22-23% protein | Proline | A modest food portion covers this narrow mass balance. |
| **Whey protein** | 21.9-32.8 g | ~24-37 g WPI90 or ~27-41 g WPC80 | Glycine | A normal shake supplies enough glycine by mass at the upper end, despite low concentration. |

### Sensitivity to unknown routing efficiency

The table assumes 100% absorption and 100% routing of the relevant amino acids to collagen. If only 50% were routed, every amount would double. Human studies do not provide a defensible universal routing percentage, so 50% is an illustration, not an estimate.

- **Why collagen can still differ:** it creates higher, faster glycine/proline exposure and provides hydroxyproline-containing peptides that may signal.
- **Why ordinary protein can still work:** endogenous collagen synthesis uses the shared amino-acid pool; vegans do not lose the biochemical ability to produce collagen.
- **Why 30 g may outperform the mass floor:** the dose could change peak exposure, peptide signaling or distribution, or the benefit could reflect trial-specific factors rather than simple replacement of 2-3 g turnover.

TURNOVER CEILING

# Is there a maximum daily collagen production rate?

No validated universal maximum has been established in healthy adult humans.

### What is available

A basal whole-body turnover estimate (~2-3 g/day), tissue-specific FSR values, serum markers, and long-term structural changes.

### What is missing

A graded nutrient study that measures absolute whole-body collagen synthesis in grams/day plus breakdown and tissue destination.

### Why one number is unlikely

Skin, bone, tendon, lung and healing tissue have very different pool sizes, turnover rates and responses to injury, age and loading.

### Maximum vs normal

Wound healing, growth, fibrosis and disease can raise production/turnover. Those states do not define a safe or useful athletic maximum.

| Common number | What it means | Why it cannot be used as a maximum |
|---|---|---|
| **2-3 g/day** | Estimated normal whole-body collagen turnover from hydroxyproline metabolism | A historical average/estimate; not measured after maximal loading or supplementation. |
| **0.5-2%/day** | Review-level range for turnover of some collagen-containing protein pools | Tissue-specific percentages cannot be safely multiplied by a single total-body collagen pool. |
| **FSR in %/h** | Short-term tracer incorporation in a sampled tissue fraction | Requires the actual active protein pool to convert to grams and does not include breakdown. |
| **PINP AUC** | Systemic marker exposure over hours | No validated conversion from PINP units to grams of tendon collagen. |

### Most honest answer

We can calculate the amino-acid mass contained in a plausible basal turnover flux. We cannot calculate the optimal collagen dose from a known maximum production ceiling, because that ceiling has not been measured.

VEGAN / VEGETARIAN EVIDENCE

# Avoiding dietary collagen does not stop endogenous collagen synthesis

However, direct vegan-versus-omnivore tendon synthesis data are a major evidence gap.

| Evidence | Population / method | Finding | What it means for collagen |
|---|---|---|---|
| **Danish cross-sectional study** | 78 vegans and 77 omnivores; serum PINP, BAP, CTX, osteocalcin, vitamin D and PTH | Adjusted PINP was 32% higher and BAP 58% higher in vegans; CTX was 30% higher with P=0.06. Vegans had lower vitamin D and higher PTH. | Vegans clearly still produce type-I procollagen. Higher PINP likely reflected higher bone turnover, not superior tendon synthesis. |
| **Vegetarian child studies** | Bone-turnover markers and DXA | Some studies report higher bone turnover; findings vary with calcium, vitamin D, growth and body composition. | Bone markers cannot answer tendon FSR or matrix quality. |
| **Direct tendon FSR comparison** | Vegans vs omnivores | No qualifying human tendon-biopsy or tendon-FSR comparison was located. | We cannot claim equal or reduced tendon synthesis from current evidence. |
| **Dietary mechanism** | No animal collagen intake | Collagen is synthesized from absorbed and endogenous amino acids, including from plant proteins. | Dietary collagen is not an essential nutrient; adequate total protein, lysine, vitamin C, minerals and energy still matter. |

### Why the vegan study is not proof against supplements

A high PINP value can accompany high bone turnover and poorer calcium/vitamin-D status. It is not evidence of a stronger tendon or optimal collagen deposition. The study is useful only for rejecting the claim that dietary collagen is required for the body to make type-I procollagen.

- **Best current inference:** well-planned vegan diets can provide all indispensable amino acids and vitamin C needed for endogenous collagen synthesis.
- **Unanswered question:** whether collagen-specific peptides or acute glycine exposure provide a tendon advantage over isonitrogenous plant protein in trained humans.
- **Needed trial:** vegan participants randomized to plant protein + vitamin C, matched free glycine/proline/lysine + vitamin C, fermentation-derived collagen-like protein, and placebo, with tendon biopsy/tracer and long-term mechanics.

*Hansen et al. Bone turnover, calcium homeostasis, and vitamin D status in Danish vegans. Eur J Clin Nutr. 2018;72:1046-1054. DOI: 10.1038/s41430-017-0081-y.*

PRACTICAL INTERPRETATION

# Is collagen supplementation meaningful or mostly marketing?

The defensible answer is neither “essential” nor “useless.”

### Strongly supported

Progressive tendon loading is the primary adaptation signal. Complete protein remains the priority for muscle and general protein adequacy.

### Reasonably supported

15-30 g collagen/gelatin paired with loading can raise systemic markers; several 30 g chronic trials improved tendon mechanics/size.

### Plausible but unproven

Five grams collagen added to whey may be enough to correct glycine availability; specific collagen peptides may have signaling effects.

### Not supported

That serum PINP equals collagen deposited in a tendon; that 30 g is a known saturation dose; that proline + vitamin C alone switches on collagen synthesis.

| Goal | Most defensible nutrition choice | Reason |
|---|---|---|
| **Muscle hypertrophy** | Adequate total protein + high-quality complete protein such as whey, dairy, eggs, meat, soy or a well-designed plant blend | Leucine and essential amino acids drive muscle protein synthesis; collagen is inferior here. |
| **Tendon-focused training block** | Optionally add 10-15 g collagen as a conservative protocol, or 30 g where matching higher-dose trials is the priority; ensure vitamin-C adequacy | Collagen is a concentrated gly/pro source; long-term tendon evidence is strongest with loading and several higher-dose protocols. |
| **Hybrid muscle + connective strategy** | Keep the full complete-protein dose and add collagen rather than replacing most of the whey; 25+5 is a tested blend for amino-acid availability and muscle-connective FSR vs placebo | Preserves leucine/EAA while increasing glycine, but superiority over whey alone is unproven. |
| **Vegan strategy** | Adequate total plant protein, lysine-rich foods/soy, vitamin C, energy and micronutrient adequacy; collagen-specific supplementation is optional only if using fermentation-derived products | No evidence shows vegans cannot synthesize collagen; direct tendon-comparison evidence is missing. |

### Vitamin C dose

Vitamin C is indispensable when deficient, but megadosing is not established as superior when status is adequate. Trials commonly use 50 mg, 500 mg, or vitamin-C-enriched products. The evidence supports adequacy and matched controls more clearly than “more is better.”

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### Reading the Level 5 evidence

No single trial answers whether collagen is superior to an equal dose of whey, soy or free amino acids for tendon adaptation. Most direct trials compare collagen protein with carbohydrate placebo while matching training and sometimes vitamin C.

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### Research gap that would most improve the answer

A properly powered trial should match calories, total protein/nitrogen, essential amino acids and vitamin C; compare collagen with whey/soy and free glycine+proline+lysine; measure tendon-specific tracer incorporation; follow long-term tendon mechanics; and monitor habitual diet throughout.