

Acute effects of four stretching modalities on range of motion, agility, and power: A systematic review



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ABSTRACT

Pre-exercise stretching is near-universal in sport and rehabilitation, yet the comparative acute effects of static (SS), dynamic (DS), proprioceptive neuromuscular facilitation contract-relax (PNF-CR), and contract-relax antagonist-contract (CRAC) stretching on range of motion (ROM), agility, and power remain unresolved, with CRAC underrepresented in comparative research. This review compared the acute, single-session effects of the four modalities in healthy adults and youth. Seven databases were searched (January 1985–May 2025) with backward citation chasing; single-session studies measuring ROM, agility, or power immediately post-stretch were eligible, and risk of bias was appraised with PEDro, JBI, NOS, and AMSTAR-2. Seventeen studies were synthesised narratively. For ROM, CRAC produced the largest acute gains (37–47% for hamstrings), followed by PNF-CR $\geq$ SS > DS. DS was most consistently superior for agility and power; SS impaired both at ≥ 60 s per muscle; PNF-CR impaired power near-maximally. CRAC preserved agility and power at single-muscle, submaximal dosing. Contraction intensity (15–25% MVC) and the number of muscle groups emerged as candidate moderators. Evidence that multi-muscle CRAC simultaneously improves all three domains rests on a single Level IV study and requires confirmation by an adequately powered four-arm randomised trial.

Keywords: CRAC stretching; range of motion; agility; power; warm-up; neuromuscular facilitation.

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INTRODUCTION

Stretching before physical activity is among the most widely practised components of athletic preparation, performed with the expectation that it will increase joint range of motion (ROM), prepare the neuromuscular system, and reduce musculotendinous injury risk. Despite its ubiquity, the acute stretching literature is among the most contested in sport science, with the dominant paradigm shifting markedly over three decades (Behm et al., 2016).

Four modalities are compared here. Static stretching (SS) involves passive elongation to mild discomfort, held 15–90 s. Dynamic stretching (DS) involves controlled repetitive movement through range without an end-range hold, combining mechanical, thermogenic, and neural effects. PNF contract–relax (PNF-CR) involves a 6–10 s isometric contraction of the target muscle followed by passive elongation, historically attributed to autogenic inhibition via Golgi tendon organ activation, although direct neurophysiological evidence for this mechanism is limited (Hindle et al., 2012; Sharman et al., 2006). CRAC adds a second active phase: after the target-muscle contraction and relaxation, the antagonist performs a concentric contraction that deepens the stretch via reciprocal Ia inhibition (Osternig et al., 1990). CRAC thus engages two inhibitory pathways, proposed to account for its acute ROM superiority (Hindle et al., 2012). A continuous-contraction variant of CRAC — termed contract–reciprocal-contrast (CRC) — omits the relaxation phase and underlies the multi-muscle performance findings examined here (Millner et al., 2022).

Acute ROM change is attributed to peripheral reductions in musculotendinous-unit (MTU) stiffness and, more dominantly, to increased stretch tolerance — a central increase in willingness to accept passive load at end range (Magnusson et al., 1996; Weppeler & Magnusson, 2010). The stretch-induced performance deficit associated with SS and PNF-CR is linked to reduced muscle-spindle sensitivity, H-reflex suppression (Saito & Mizuno, 2025), and non-optimal cross-bridge kinetics after MTU lengthening (Kay & Blazevich, 2012), whereas DS avoids these deficits through temperature elevation, neural activation, and post-activation-potential-adjacent facilitation (Opplert & Babault, 2018).

No comparative review has assessed all four modalities against all three outcome domains using only single-session designs. The most-cited acute-stretching review identified only three CRAC performance studies (Behm et al., 2016), and the hypothesis that multi-muscle CRAC at submaximal intensity uniquely improves ROM, power, and agility simultaneously has never been formally synthesised. The primary question was how single-session SS, DS, PNF-CR, and CRAC compare for acute ROM, agility, and power in healthy adults and youth. Secondary questions were whether contraction intensity and the number of muscle groups stretched moderate CRAC outcomes, and whether CRAC can achieve simultaneous improvement across all three domains. A practical, goal-based framework is presented in Table 1, with the combined-modality protocol explicitly flagged as requiring randomised confirmation.

MATERIAL AND METHODS

Search strategy and study selection

Seven databases were searched from January 1985 to May 2025 (PubMed/MEDLINE, Scopus, SPORTDiscus, Web of Science, Cochrane CENTRAL, CINAHL, EMBASE). The 1985 lower bound captured Etnyre and Abraham (1986), the earliest identified acute CRAC comparison. Modality terms (static, dynamic, PNF, CRAC, CRC, contract-relax antagonist-contrast, hold-relax, agonist-contrast) were combined with outcome terms (range of motion, flexibility, agility, change of direction, power, sprint, jump, countermovement). Backward citation chasing was applied to all eligible studies and to five anchor papers

(Behm et al., 2016; Burgess et al., 2019; Hindle et al., 2012; Millner et al., 2022; Sharman et al., 2006). The full Boolean strategy and per-database yields are provided as a supplementary file (Appendix B).

Table 1. Proposed goal-based acute warm-up framework.

Goal	Modality	Dose / intensity	Evidence
Maximum ROM (clinical)	CRAC, multi-muscle	10 s isometric + 10 s concentric ×3; 15–25% MVC	Burgess et al. (2019); Feland & Marin (2004); Millner et al. (2022)
Power & agility pre-competition	Dynamic stretching	2–3 sets × 15 reps, full ROM	Abd Malek et al. (2024); Ltifi et al. (2023); Perrier et al. (2011)
ROM + power + agility (hypothetical)	CRAC then DS	Submaximal CRAC, then dynamic warm-up; randomised confirmation required	Cheurlin et al. (2025); Millner et al. (2022)
ROM without power penalty	SS ≤30 s/muscle	30 s × 2–3	Behm et al. (2016); Kay & Blazevich (2012); Pinto et al. (2014)
Postural stability	CRAC, 3 groups	7 s isometric + concentric ×3	Ryan et al. (2010)

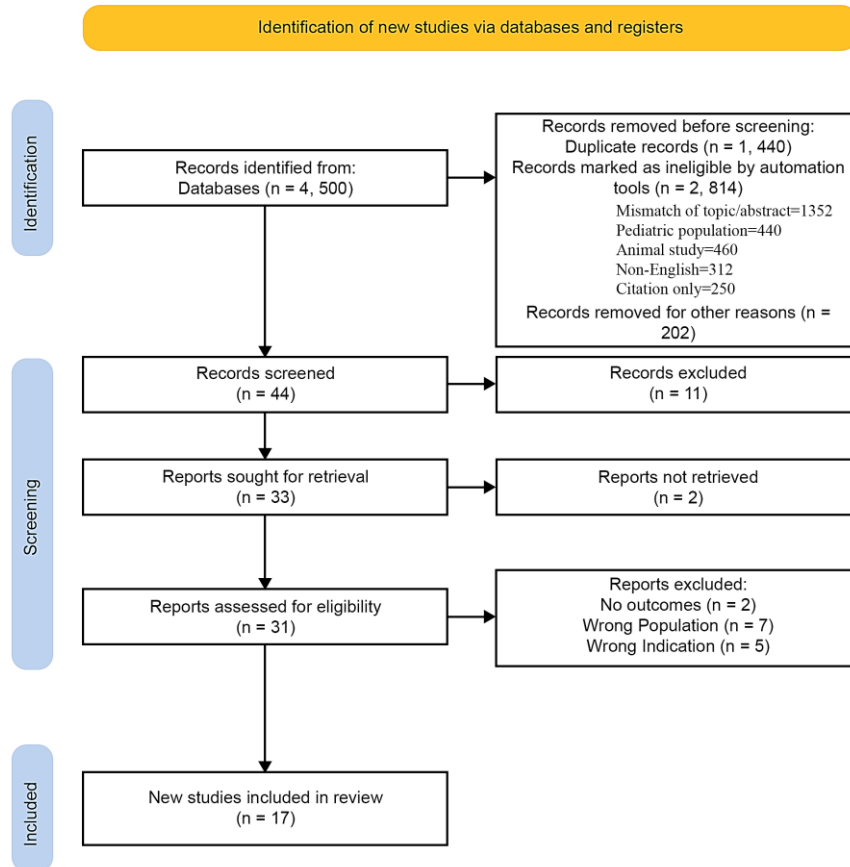


Figure 1. PRISMA 2020 flow diagram of study identification, screening, eligibility assessment, and inclusion.

Inclusion required: (a) a single-session acute design; (b) pre-to-post measurement of at least one of ROM, agility, or power immediately after stretching; (c) at least one of the four target modalities; (d) healthy adult or youth participants; and (e) peer-reviewed English-language publication. Multi-session interventions, clinical-only populations without a healthy comparator, and reports without extractable acute data were

excluded. Database searching identified 4,500 records. After removal of duplicates ($n = 1,440$), automation-based exclusions ($n = 2,814$), and other ineligible records ($n = 202$), 44 records were screened; 33 full-text reports were sought (2 not retrieved) and assessed for eligibility, yielding 17 studies for synthesis (Figure 1). Systematic reviews and mechanistic papers were retained as contextual references rather than included studies. Three frequently cited reports were excluded from the included set with reasons: two were multi-session interventions (a 6-week shoulder-ROM trial and an 8-week hamstring trial) and one studied a clinical population (chronic low-back pain) without a healthy comparator.

Participants and outcome measures

Included studies involved healthy adult or youth participants, ranging from recreationally active adults and university students to professional and elite athletes in soccer, basketball, wrestling, and gymnastics. ROM was assessed by sit-and-reach, passive straight-leg raise, active knee extension (AKE), goniometry, and inclinometry. Agility was measured by the Illinois Agility Test (IAT), T-test, 505 change-of-direction test, and L-run; the IAT has excellent test-retest reliability ($ICC = 0.98$) in male team-sport athletes (Hachana et al., 2013). Power was assessed by countermovement jump (CMJ) height, standing long-jump distance, 5-step jump, 10–30 m sprint time, and isokinetic peak torque. Post-stretch assessment timing ranged from immediately post-stretch to 15 min across studies.

Quality appraisal and extraction

Randomised and crossover trials were appraised with the PEDro scale (≥ 5 = adequate), quasi-experimental and case designs with the JBI checklist, non-randomised comparisons with the Newcastle–Ottawa Scale, and systematic reviews with AMSTAR-2. The Millner et al. (2022) case study ($n = 7$, no control, no randomisation) was retained for its unique three-domain CRAC data and is designated Level IV evidence throughout. Participants, protocol (modality, muscle groups, dose, contraction intensity), outcomes, assessment timing, percentage change, and effect sizes (Cohen's d or η^2 where reported) were extracted. Appraisal outcomes are reported in the Appendix A.

RESULTS

Range of motion

All four modalities produced significant acute ROM gains over control; the hierarchy was CRAC > PNF-CR $\geq$ SS > DS at equivalent volumes (Table 2). A meta-analysis confirmed that a single SS bout significantly increased sit-and-reach, passive straight-leg-raise, and AKE ROM, with effects lasting up to 30 min (Behm et al., 2023). In a randomised crossover, SS and PNF produced equivalent hamstring ROM gains ($\eta^2 = .59-.68$), though only PNF reduced biceps femoris shear modulus ($p = .045$), consistent with stretch tolerance as the dominant acute mechanism (Železnik et al., 2024). SS intensity did not alter ROM gains when duration was equated (Bryant et al., 2023), and 90-s SS produced no CMJ impairment in female gymnasts, suggesting high-ROM populations may be protected from power deficits (Donti et al., 2021).

DS produced smaller ROM gains than SS or PNF, primarily via temperature elevation and transient stiffness reduction (Opplert & Babault, 2018). A four-condition trial quantified acute hamstring gains of +7.5% (CRAC), +4.1% (SS), and +2.7% (DS) (Cheurlin et al., 2025), and a meta-analysis found a non-significant standardised mean difference for DS versus control (Freitas et al., 2024). PNF-CR consistently matched or exceeded SS: a landmark review concluded PNF is the most effective technique for short-term ROM, with antagonist-contraction (“active”) techniques achieving the greatest gains (Sharman et al., 2006). Osternig et al. (1987) found agonist contract-relax (ACR, i.e., CRAC) produced 3–6% greater knee extension than contract-relax despite 71–155% greater hamstring EMG — ROM gains occurring while the target muscle was under

substantial tension. A meta-analysis of 39 trials confirmed hold-relax and contract-relax were both superior to control for immediate hamstring flexibility (Cayco et al., 2019).

In the largest acute CRAC trial ($n = 40$), a 6-s maximal isometric contraction followed by concentric contraction against manual resistance, repeated three times, improved AKE ROM by 37%, maintained for eight minutes (Burgess et al., 2019). Extending the protocol to seven muscle groups at 15% isometric intensity, the Level IV case study recorded a mean 47% sit-and-reach improvement (Millner et al., 2022). A third independent comparison confirmed that CRAC produced the largest ROM gain of any condition tested (+7.5%; Cheurlin et al., 2025). Across modalities, CRAC's advantage was most pronounced for multi-joint muscles and multi-muscle protocols (Table 2).

Table 2. Acute range-of-motion outcomes by modality (included primary studies).

Study	n	Modalities	ROM outcome
Etnyre & Abraham (1986)	12	SS, CR, CRAC	CRAC > CR > SS (ankle dorsiflexion)
Osternig et al. (1990)	30	SR, CR, ACR	ACR +9–13% knee ext. vs CR/SR; 89–110% ↑ EMG
Osternig et al. (1987)	10	SR, CR, ACR	ACR +3–6% knee ext. vs CR/SR; 71–155% ↑ EMG
Ford & McChesney (2007)	32	CRAC, SS, AC	All ↑ AKE; gains held 25 min; no method superior
Burgess et al. (2019)	40	CRAC vs rest	AKE +37%, held 8 min (RCT)
Millner et al. (2022) †	7	CRAC, 7 groups	Sit-and-reach +47% (Level IV)
Cheurlin et al. (2025)	37	SS, DS, CRAC, control	CRAC +7.5%, SS +4.1%, DS +2.7%
Železnik et al. (2024)	16	SS vs PNF	Equal ROM ($\eta^2 = .59 - .68$); PNF ↓ shear modulus

Note. † Level IV evidence (case study, $n = 7$, no control, no randomisation). AKE = active knee extension; ACR = agonist contract-relax (CRAC); CR = contract-relax; SR = stretch-relax; SS = static stretching; DS = dynamic stretching; PNF = proprioceptive neuromuscular facilitation.

Agility

DS consistently produced the greatest acute change-of-direction improvements. DS significantly improved IAT time (13.95 s) versus SS (14.90 s) in professional soccer players ($p < .001$; Amiri-Khorasani et al., 2010). Testing five protocols in U-17 players, DS improved IAT versus all other conditions ($\eta^2 = .56 - .73$; Ltfi et al., 2023). DS also produced significantly better shuttle-run and 5-step-jump performance than SS in military cadets, with SS no better than no warm-up on two of three tests (McMillian et al., 2006). The mechanism involves neural readiness, temperature elevation, and rehearsal of coordination patterns (Opplert & Babault, 2018).

SS impaired agility at doses >60 s/muscle, particularly in trained athletes (Chatzopoulos et al., 2014). However, SS did not impair agility when embedded in a comprehensive warm-up (Chaouachi et al., 2010), and short-duration SS (<20 s/muscle) did not impair, and sometimes improved, agility in moderately trained participants (Kalyoncu & Sogut, 2021). PNF-CR produced neutral-to-positive agility outcomes: PNF improved T-test agility within groups in youth basketball (Çetinkaya et al., 2025), and of 14 acute PNF studies, 11 showed no agility or performance decrease (Behm et al., 2016).

For CRAC, three maximal-intensity repetitions to the hamstrings produced a 37% ROM gain with no change in IAT ($p > .05$) or sprint time (Burgess et al., 2019), confirming maximal ROM gains are achievable without the agility penalty of prolonged SS or high-intensity PNF-CR. CRAC of the hamstrings, plantar flexors, and hip flexors significantly improved mediolateral postural stability ($p < .05$), attributed to neurological facilitation and antagonist irradiation (Ryan et al., 2010). The Level IV protocol recorded a mean 4% improvement in L-run time across seven muscle groups (Millner et al., 2022). The contrast between single-muscle CRAC preserving agility and multi-muscle CRAC improving it suggests the number of muscle groups is a candidate moderator (Table 3).

Table 3. Acute agility outcomes by modality (included primary studies).

Study	Test	Result
Amiri-Khorasani et al. (2010)	IAT	DS 13.95 s < SS 14.90 s ($p < .001$)
Ltifi et al. (2023)	IAT	DS best of 5 conditions ($\eta^2 = .56 - .73$)
McMillian et al. (2006)	Shuttle; 5-step jump	DS best on all tests; SS $\approx$ no warm-up
Burgess et al. (2019)	IAT	No change with 37% ROM gain (RCT)
Ryan et al. (2010)	Force plate	CRAC $\uparrow$ mediolateral stability (RCT)
Millner et al. (2022) $\dagger$	L-run	-4.4% time (improved) (Level IV)
Çetinkaya et al. (2025)	T-test	PNF $\uparrow$ within-group ($p = .05$)

Note. $\dagger$ Level IV evidence. IAT = Illinois Agility Test.

Power

DS produced the most consistent acute power improvements. DS improved CMJ height (+3.32%, $p = .002$) and 30-m sprint (+1.05% faster, $p = .002$) versus control, outperforming PNF on both (Abd Malek et al., 2024). CMJ heights were 43.0 cm (DS), 41.9 cm (SS), and 41.4 cm (no stretch; $p = .004$; Perrier et al., 2011), and fast-tempo DS produced the greatest reactive-strength and jump improvements in wrestlers (Kurt et al., 2024).

SS produced dose-dependent deficits: a mean acute power change of -3.7% across more than 100 studies, with -4.6% at ≥ 60 s/muscle versus -1.1% for shorter durations (Behm et al., 2016). 60-s SS reduced CMJ height (-3.4%) and average power (-2.7%), while 30-s SS produced no deficit (Pinto et al., 2014). Detrimental SS effects are mainly limited to longer durations not typical of pre-exercise routines (Kay & Blazevich, 2012). PNF-CR power outcomes were strongly moderated by contraction intensity (mean -4.4%; Behm et al., 2016): near-maximal PNF impaired maximal strength and volume via fast-twitch fatigue (Barroso et al., 2012), whereas at moderate intensity PNF improved CMJ (+1.53%, $p = .048$; Abd Malek et al., 2024). Submaximal contract-relax PNF at 20%, 60%, and 100% MVC produced equivalent ROM gains, implying full ROM benefit is attainable without the power cost of near-maximal effort (Feland & Marin, 2004).

Table 4. Acute power outcomes by modality (included primary studies).

Study	Test	Result
Behm et al. (2016) (review)	Multiple	SS -3.7%; DS +1.3%; PNF -4.4%; ≥ 60 s SS = -4.6%
Pinto et al. (2014)	CMJ	60-s SS -3.4% height; 30-s SS no deficit
Abd Malek et al. (2024)	CMJ; sprint	DS +3.32% CMJ; PNF +1.53% CMJ
Barroso et al. (2012)	1RM; volume	Near-maximal PNF impaired strength/volume
Burgess et al. (2019)	20-m sprint	No change (single-muscle, maximal CRAC)
Millner et al. (2022) $\dagger$	Long jump	+10% (up to +16.85%) (Level IV)
Cheurlin et al. (2025)	CMJ	CRAC -3.2% = SS = control; DS +0.4%; no re-warm-up recovery

Note. $\dagger$ Level IV evidence. MVC = maximal voluntary contraction; CMJ = countermovement jump.

For CRAC, contraction intensity was the critical protocol variable. Using a maximal isometric contraction on a single hamstring group, no sprint change accompanied the 37% ROM gain — single-muscle CRAC preserved power regardless of intensity (Burgess et al., 2019). Using 15% intensity across seven muscle groups, the Level IV study recorded a mean +10% standing-long-jump improvement (up to +16.85%), proposed to reflect motor-unit recruitment at previously unattained end-range positions (Millner et al., 2022). Critically, in the most rigorously controlled comparison ($n = 37$, four conditions), CMJ height decreased significantly ($p < .05$) after CRAC (-3.2%), SS (-2.3%), and no-stretch control (-2.3%) and was unchanged after DS (+0.4%); no further change occurred after a re-warm-up (Cheurlin et al., 2025). Because the decrement was equal to the no-stretch control and was not reversed by re-warm-up, it reflects the warm-up/testing context rather than a CRAC-specific effect; the authors concluded stretching had no major effect on jump within a warm-up and recommended CRAC when flexibility is the goal (Cheurlin et al., 2025). This

does not refute the Level IV power gain but indicates it is attributable to multi-muscle scope and submaximal intensity rather than the CRAC sequence per se (Table 4).

DISCUSSION

Four findings emerge. First, CRAC consistently produces the largest acute ROM gains, confirmed across primary studies spanning 1986–2025. Second, DS remains the evidence-based recommendation for pre-competition agility and power. Third, contraction intensity is the primary determinant of CRAC and PNF-CR performance outcomes: submaximal contractions (15–25% MVC) produce equivalent ROM gains without fast-twitch fatigue (Barroso et al., 2012; Feland & Marin, 2004). Fourth, the number of muscle groups appears to be a previously unrecognised candidate moderator: single-muscle CRAC preserves agility and power, whereas multi-muscle CRAC at submaximal intensity may improve both — although this rests on Level IV evidence. Hence, all findings pertaining to CRAC should be considered as hypothesis-generating within the discussion.

The dissociation between ROM and performance is practically important. The largest single-group CRAC ROM gain (+37%) occurred with zero agility or sprint impairment (Burgess et al., 2019), indicating ROM and performance mechanisms are not tightly coupled acutely. A proposed explanation is that stretch tolerance drives ROM centrally, while agility draws on peripheral activation that CRAC's reciprocal inhibition may facilitate rather than suppress (Magnusson et al., 1996; Weppeler & Magnusson, 2010).

The most important new constraint on the CRAC–power claim is the four-condition trial showing CRAC reduced CMJ to the same degree as SS and no-stretch control, with no re-warm-up recovery (Cheurlin et al., 2025). Framing this result as a CRAC-specific deficit reversible by re-warm-up is not supported by the data; the equal control decrement indicates the effect is contextual. The multi-muscle hypothesis remains a valid explanatory framework for the Level IV power gain but requires prospective testing.

Moderators warrant acknowledgement. In particular both sex and training status are observed to play a role according to select studies. The former is a critical gap: primary acute CRAC studies used male or mixed-sex samples despite evidence that females show greater acute stiffness reduction per session (Yu et al., 2022). Training status moderates the SS agility deficit, with highly trained athletes more susceptible (Kalyoncu & Sogut, 2021). Additionally, assessment timing introduces heterogeneity: ROM effects peak 5–10 min post-stretch while power deficits typically maximise immediately, so timing windows can reverse apparent conclusions. These moderators demand a broader conceptual model that can integrate all these findings. Since acute outcomes emerge from the interaction of modality, contraction intensity, volume, muscle-group scope, and timing, a framework for tailoring stretching protocols is proposed in Figure 2.

Warm-up theory/Neuromuscular readiness/Movement preparation

Stretching modalities should be described not as isolated techniques but as parts of a broader warm-up framework that combines mobility, neuromuscular readiness, and performance preparation. Contemporary warm-up theory emphasizes three overlapping goals. Firstly, enhancing range of motion to permit safe movement. Secondly, priming neuromuscular pathways for rapid activation. Thirdly, optimizing acute performance capacity. It should be noted that each modality contributes differently to these goals.

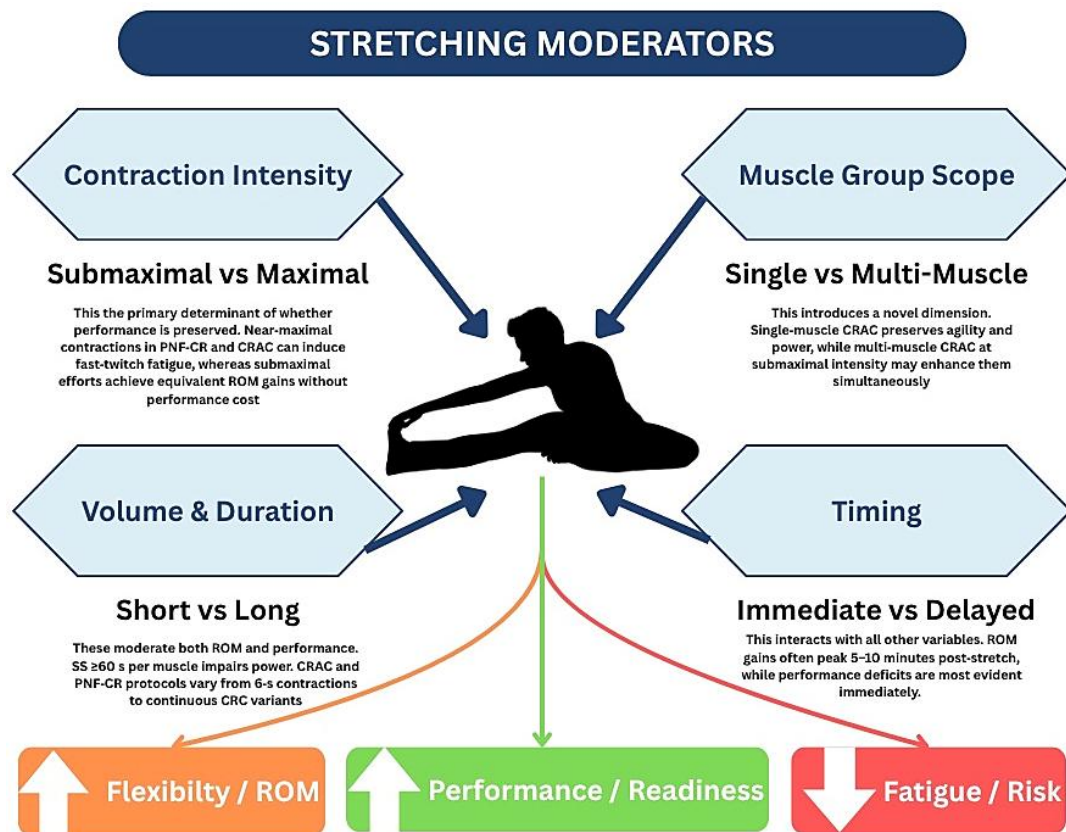


Figure 2. Goal-based framework linking acute stretching modalities with mobility, neuromuscular readiness, and performance preparation.

Focusing on SS, this primarily serves the mobility objective. Short bouts (<30 s per muscle) reliably increase ROM without meaningful performance cost, making SS useful when flexibility is a prerequisite for safe execution (a good example is in gymnastics or dance). However, longer durations (>60 s) can impair neuromuscular power. This goes to show that SS should be integrated within a comprehensive warm-up rather than used alone.

In comparison, DS aligns most closely with neuromuscular readiness. By combining temperature elevation, rehearsal of sport-specific movement patterns, and facilitation of motor-unit recruitment, DS consistently enhances agility and power. Within a movement-preparation framework, DS functions as the connection between mobility work and performance-specific drills. What this means is that it is the evidence-based choice when explosive output is the priority such as in weightlifting or construction work.

PNF contract-relax occupies an intermediate role though. At moderate contraction intensities, PNF-CR can improve ROM while preserving performance, but near-maximal efforts induce fast-twitch fatigue and impair power. Thus, PNF-CR is best conceptualized as a targeted mobility tool within warm-ups where flexibility gains are required but performance demands are moderate. A good example is in pre-sports warmups.

CRAC stretching offers the most pronounced acute ROM gains, particularly in multi-muscle protocols. Importantly, when performed at submaximal intensity, CRAC can preserve or even enhance agility and power, though its application in the examples described previously have yet to be properly explored. Still,

within a movement-preparation system, CRAC is positioned as a dual-purpose technique: maximising ROM while maintaining readiness, though current evidence is limited and heterogeneous.

Future research framework

While the present synthesis identifies contraction intensity and muscle-group scope as novel moderators of acute stretching outcomes, the evidence for multi-muscle CRAC remains limited. To advance the field, future research should adopt a structured framework that systematically manipulates these moderators within controlled designs (Figure 3).

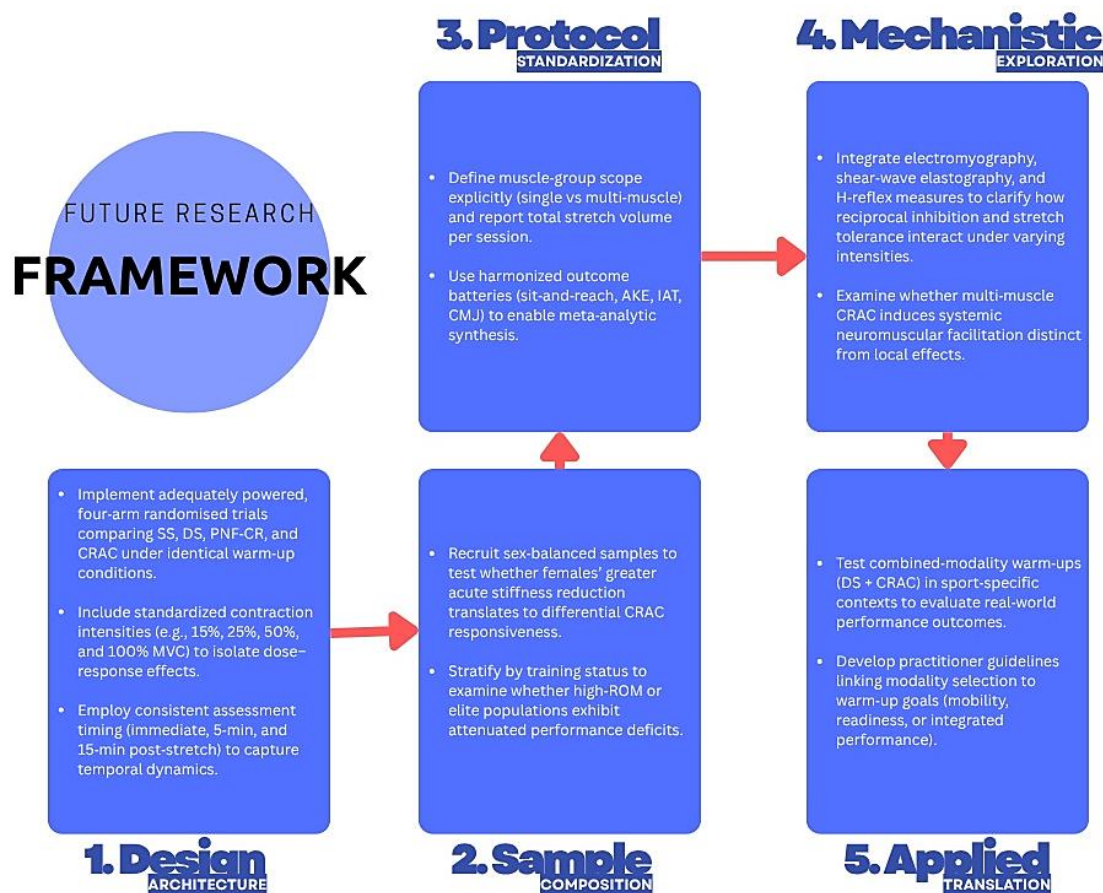


Figure 3. Proposed framework for future research on moderators of acute stretching outcomes.

CONCLUSIONS

All four modalities produce significant acute ROM gains but CRAC produces the largest (37–47% for hamstrings), most pronounced for multi-joint muscles and multi-muscle protocols; however, this should be taken as preliminary evidence. What is established though is that DS is the recommendation when agility and power cannot be compromised. Additionally, SS ≤ 30 s/muscle is safe within comprehensive warm-ups; ≥ 60 s produces clinically relevant deficits. Lastly, PNF-CR is positive at moderate intensity and impairs power near maximally. While CRAC preserves agility and power at single-muscle, submaximal dosing; evidence that multi-muscle CRAC simultaneously improves all three domains is limited to one Level IV case study and is constrained by a controlled trial showing a context-dependent CMJ decrement. CRAC as a promising but still under-investigated modality and more studies are needed to determine its superiority. An adequately

powered four-arm randomised trial comparing all modalities across ROM, agility, and power — with standardised contraction intensity, the relaxation phase as an independent variable, post-stretch re-warm-up conditions, and female-inclusive sampling — is the most urgent research need.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows:

Conceptualization: Rod Millner. Methodology: Rod Millner. Investigation: Rod Millner. Data curation: Rod Millner. Writing – original draft: Rod Millner. Formal analysis: Faraz Ahmed Bokhari. Writing – review & editing: Faraz Ahmed Bokhari. Supervision: Faraz Ahmed Bokhari.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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CONFLICT OF INTEREST

One author provides commercial flexibility-coaching services that incorporate CRAC/CRC techniques and is an author of the primary case study (Millner et al., 2022) on which several conclusions draw. The systematic search and full manuscript were conducted independently of that commercial interest, and the included-study criteria and appraisal were applied uniformly. These relationships did not alter the appraisal criteria, and readers should weigh them when interpreting the review's conclusions.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, AI-assisted tools were used to support the literature-identification phase, to produce an initial outline used only as a drafting guide, and subsequently to assist with accuracy-checking, reference verification, and copy-editing. The reproducible database search reported in the supplementary file is the method of record. The named authors directed the work, verified all data and citations against primary sources, and take full responsibility for the content. AI tools are not, and cannot be, listed as authors.

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APPENDIX A. RISK-OF-BIAS / QUALITY APPRAISAL

Table A1. PEDro appraisal (randomised and crossover trials).

Study	Design	PEDro (/10)	Quality	Notes
Abd Malek et al. (2024)	Randomised crossover (3 conditions)	7	Good	Randomisation, concealed allocation, baseline comparability, blinded assessor, adequate follow-up
Barroso et al. (2012)	Within-subject randomised (8 sessions)	6	Fair	Randomisation and blinding adequate; small sample lowers external validity
Burgess et al. (2019)	RCT (2 groups)	7	Good	Randomisation, baseline comparability, assessor blinding; short-term outcomes only
Çetinkaya et al. (2025)	RCT (2 groups)	6	Fair	Randomisation and control present; no blinding; small youth sample
Cheurlin et al. (2025)	Randomised crossover (4 conditions)	7	Good	Randomisation, repeated-measures control; assessor blinding unclear
Ford & McChesney (2007)	RCT (4 groups)	7	Good	Randomisation, baseline comparability, assessor blinding; short-term only
Ltifi et al. (2023)	Randomised crossover (5 conditions)	7	Good	Randomisation, repeated-measures; assessor blinding unclear
McMillian et al. (2006)	Randomised crossover (3 conditions)	7	Good	Randomisation, counterbalanced order; assessor blinding unclear
Ryan et al. (2010)	Randomised repeated-measures (3 conditions)	6	Fair	Randomisation and control; assessor blinding unclear

Table A2. JBI appraisal (quasi-experimental / case designs).

Study	Design	JBI (/9)	Quality	Notes
Osternig et al. (1987)	Experimental (EMG + ROM)	7	Good	Clear protocol, objective measures, reproducible; small sample
Millner et al. (2022)	Case study (single-day)	5	Moderate	Objective measures; no control group; limited generalisability (Level IV)

Table A3. AMSTAR-2 appraisal (systematic reviews).

Study	Design	AMSTAR-2	Quality	Notes
Behm et al. (2016)	Systematic review	High	Comprehensive	Clear inclusion criteria, duplicate screening, risk-of-bias assessment, qualitative synthesis
Behm et al. (2023)	Systematic review + meta-analysis (47 studies)	High	Comprehensive	Robust search, effect-size pooling, heterogeneity analysis, GRADE confidence reporting

Table A4. Newcastle–Ottawa Scale appraisal (non-randomised comparisons).

Study	Design	NOS (/9)	Quality	Notes
Amiri-Khorasani et al. (2010)	Within-subject repeated measures	6	Moderate	Clear protocol, objective timing; no randomisation or blinding

Note. Figure 1 (PRISMA 2020 flow diagram) is supplied as a separate image file. The full Boolean search strategy, per-database yields, and the complete data-extraction grid are supplied as supplementary files.

APPENDIX B. STUDY CHARACTERISTICS AND DATA-EXTRACTION GRID

Study	Year	Design	Sample	Population	Modality	Muscle/Groups	Protocol	ROM Outcome	Agility Outcome	Power Outcome	Moderators	Key Findings	Limitations
Abd Malek et al.	2024	Randomized crossover, 3 conditions (DS, PNF, control)	n = 30	Recreationally active men, mean age 23.3	Dynamic stretching vs. PNF	Hamstrings, quadriceps, gluteus, groin	DS: rhythmic movements (lunges, squats, butt-kicks, etc.); PNF: contract-relax-agonist-contraction, 3 reps × 10s with assistance	Not assessed	Not assessed	DS: +3.32% CMJ, +1.05% faster sprint ($p = .002$); PNF: +1.53% CMJ ($p = .048$), +0.35% faster sprint ($p = .049$)	Protocol intensity (maximal contraction in PNF vs. active movement in DS); recovery period 72h between sessions	DS produced superior improvements in both sprint and jump compared to PNF and control; PNF still improved performance vs. control	Only male participants, small sample, short-term acute effects only
Amiri-Khorasani et al.	2010	Within-subject, repeated measures	n = 19	Professional male soccer players, mean age 22.5	Static, Dynamic, Combined, No stretch	Gastrocnemius, hamstrings, quadriceps, gluteal, adductors, abductors	SS: 30s holds; DS: 60s cycles; Combined: SS then DS; No stretch control	Not assessed	IAT times: DS 13.95s, SS 14.90s, Combined 14.50s, No stretch 14.18s	Not assessed	Experience level moderated results: more experienced players faster overall, especially with DS and no stretch	Dynamic stretching produced the fastest agility times; static stretching impaired agility; combined stretching better than SS but worse than DS	Small sample, only men, limited to acute effects
Barroso et al.	2012	Within-subject, randomized, 8 sessions	n = 12	Strength-trained young men (mean age 20.4)	Static, Ballistic, PNF vs. No stretch	Quadriceps, gluteus maximus, hamstrings	SS: 3×30s holds; BS: 1 min bobbing cycles; PNF: hold-relax (5s passive, 5s isometric, 20s passive)	All protocols ↑ ROM; PNF greatest (+4.7 cm), SS (+3.9 cm), BS (+2.9 cm)	Not assessed	1RM leg press ↓ only after PNF (-5.5%); all protocols ↓ reps (SS -20.8%, BS -17.8%, PNF -22.7%) and ↓ total volume (SS -20.4%, BS -17.9%, PNF -22.4%)	Training status (strength-trained men less affected by SS/BS, but PNF still impaired strength)	PNF impaired maximal strength; all protocols reduced endurance and volume; BS also detrimental despite prior evidence of performance benefits	Small sample, only men, acute effects only, ROM measured via sit-and-reach not directly matching leg press muscles
Behm et al.	2016	Systematic review + meta-analysis (47 studies, 110 effect sizes)	47 studies	Healthy participants, mixed sex, trained/untrained	Static, dynamic, ballistic, PNF	Hamstrings, triceps surae, hip adductors, sit-and-reach	Wide range: 5–600s, submaximal vs maximal intensity	Acute ROM ↑ small effect (SMD = 0.555); significant gains for hamstrings, triceps surae, sit-and-reach; no gain for hip adductors	Not assessed	Not assessed	No significant differences by stretch intensity, sex, trained state, or technique; age and duration not predictive	A single bout of stretching produces small but consistent ROM improvements across most tests	Moderate confidence (GRADE); heterogeneity present; only acute ROM assessed, not performance
Behm et al.	2015	Systematic review of acute stretching effects	125 studies, 270 findings	Healthy active individuals	Static, Dynamic, PNF	Primarily lower limb (hamstrings, quads, plantar flexors)	SS ≥60s → -4.6% performance; SS <60s → -1.1%; DS small-moderate improvements; PNF ~ -4.4%	All modalities improved ROM acutely (<30 min), via reduced stiffness and increased stretch tolerance	Limited agility data; DS generally favourable	Performance changes: SS -3.7%, DS +1.3%, PNF -4.4%; SS moderate benefit at long muscle lengths (+2.2%)	Duration critical (≥60s more impairing); muscle length influences outcomes; contraction type matters	DS recommended for warm-up; SS and PNF impair performance if prolonged; ROM gains consistent across modalities	Excluded non-English studies; heterogeneity; mostly immediate post-stretch testing
Burgess et al.	2019	Randomised controlled trial	n = 40	Healthy, moderately active males (21–35 yrs)	CRAC stretch vs. rest	Hamstrings	3 repetitions per leg, 6–15s isometric + 6–15s concentric, 20s rest	Active knee extension ROM ↑ 37%, maintained for 8 min	No significant change in Illinois Agility Test	No significant change in 10m or 25m sprint	BMI differed between groups but not correlated with ROM change; effect duration 8 min	CRAC produced large ROM gains without impairing agility or sprint; safe and effective pre-sport	Manual stopwatch timing; only male participants; acute effects only
Çetinkaya et al.	2025	Randomised controlled trial	n = 20 (10 passive, 10 PNF)	Male youth basketball players, ages 14–18, ≥2 years' experience	Passive static vs. PNF (hold-relax)	Hamstrings, quadriceps, calves	Passive: 3×30s holds; PNF: 5–8s isometric + relaxation + 30s passive hold, 3 reps	Not directly measured	Passive: significant improvement in T-test agility ($p = .002$); PNF: significant improvement in T-test agility ($p = .005$)	Passive: SLJ +3.1 cm ($p = .049$), Lateral jump +5.9 cm ($p = .034$); PNF: no significant change in SLJ/Lateral jump	Youth basketball context; protocol differences may explain outcomes	Passive stretching improved agility + explosive strength; PNF improved agility only; neither affected 30m sprint	Small sample size; stopwatch timing instead of photocells; no dynamic/control group; flexibility levels not stratified
Cheurlin et al.	2025	Randomised crossover, 4 conditions (SS, DS, CRAC, CTRL)	n = 37 (14F, 23M)	Young healthy adults, mean age ~20	Static, Dynamic, CRAC, Control	Hamstrings, quadriceps, plantar flexors	2×15s per muscle group, total 5 min	Flexibility ↑: CRAC +7.5%, SS +4.1%, DS +2.7%; CRAC > DS & CTRL	Not assessed	CMJ ↓ after SS (-2.3%), CRAC (-3.2%), CTRL (-2.3%); DS preserved CMJ (0.4% change); re-warm-up restored baseline	Sex differences: women had higher flexibility but lower CMJ; re-warm-up eliminated deficits	CRAC most effective for flexibility; DS best for maintaining jump height; SS and CRAC impaired CMJ acutely	Only hamstring flexibility measured; short stretch durations; vertical jump assessed only by height

DeCicco & Fisher	2005	Randomised controlled trial, 3 groups	n = 30 (10 per group)	Male and female adults, 25–50 yrs, overhand athletes (tennis, baseball, QB football)	Contract-relax-contraction (CRC), Hold-relax-contraction (HRC), Control	Shoulder external rotators	Twice weekly for 6 weeks	HRC: +13.5° ROM; CRC: +14.6° ROM; Control: +0.3°	Not assessed	Not assessed	Stretching type (CRC vs HRC)	Both CRC and HRC significantly increased external shoulder ROM; similar effectiveness	Small sample size; only shoulder ROM measured; no performance outcomes
Ford & McChesney	2007	Randomised controlled trial	n = 32 (18M, 14F)	Active college-age students (19–30 yrs)	CRAC, Static, Active Control, Control	Hamstrings	CRAC: 4 cycles (6s phases); SS: 5×30s hurdler stretch; AC: 10×10s active knee extension	All three methods ↑ AKE ROM significantly; gains maintained for 25 min; no difference between methods	Not assessed	Not assessed	Duration of effect; reciprocal inhibition may explain AC gains	Stretching (CRAC, SS, AC) produced immediate ROM gains lasting 25 min; no method superior	Small sample; only short-term ROM measured; no performance outcomes
Ltifi et al.	2023	Randomised crossover, 5 conditions	n = 12	Elite U-17 male soccer players, national division II	Static, Dynamic, Static→Dynamic, Dynamic→Static, Control	Lower-body muscles	SS & DS ~6 min; combined ~12 min	Not assessed	Dynamic stretching improved COD vs SS, combined orders; SS impaired COD vs DS; no difference DS vs control	Not assessed	Order of stretching (static→dynamic vs dynamic→static)	Dynamic stretching improved COD; static stretching detrimental; combined protocols not superior	Small sample size; only adolescent males; acute effects only
Mani et al.	2021	Pilot randomized comparative study	n = 36 (18 per group)	Sedentary males, 20–29 yrs, hamstring shortness (knee extension angle >20°)	PNF CRAC vs Static Stretching	Hamstrings	3×/week for 8 weeks; 30s per side	Both groups ↑ flexibility immediately and long-term; SS more effective acutely, equal long-term	Not assessed	Not assessed	Proprioception (position sense, motion sense)	CRAC improved motion sense significantly in long term ($p = .02$); both improved flexibility	Pilot study, small sample, only sedentary males, limited generalizability
Millner et al.	2022	Case study, single-day testing	n = 7	Active adults, 20–37 yrs, 3–5 hrs/week activity	Partner-assisted CRAC across 7 muscle groups	Chest, core, hip flexors, hamstrings, calves, ankles (inversion/eversion)	Modified CRAC: 10s isometric (15% RPE) + 10s antagonist contraction (50% RPE), repeated 3×	Sit-and-reach ↑ 47% average (2–6.5 cm gain)	L-run agility ↓ 4.4% average (0.27s faster)	Standing long jump ↑ 10% average (≈19 cm gain)	Stretching multiple muscles, reduced contraction intensity, no rest between cycles	CRAC improved flexibility, power, and agility simultaneously; contrasts with Burgess (2019) which found no performance gains	Small sample, case study design, no control group, immediate effects only
Osternig et al.	1987	Experimental study with EMG + ROM measures	n = 10 (6M, 4F)	Healthy adults, 23–36 yrs	Stretch-Relax (SR), Contract-Relax (CR), Agonist Contract-Relax (ACR)	Hamstrings, quadriceps	SR: 80s passive relax; CR: 3×5s contraction + stretch; ACR: 2×5s quadriceps contraction	ROM ↑: SR +6%, CR +4%, ACR +1%; ACR produced 3–6% greater knee extension than SR/CR despite higher hamstring EMG	Not assessed	Not assessed	EMG showed hamstring activity ↑ 43% in CR, ↑ 8% in ACR, ↓ 11% in SR	ACR yielded greatest ROM but with high antagonist tension; SR gave slightly less ROM but safest (lower EMG)	Small sample, only knee extension tested, immediate effects only
Pinto et al.	2014	Randomised crossover trial, 3 conditions	n = 16	Physically active male university students, 19–25 yrs	30s static stretch, 60s static stretch, no stretch	Calves, hamstrings, quadriceps, gluteus maximus	Partner-assisted static stretches, continuous, 30s (4 min total) vs 60s (8 min total)	Not assessed	Not assessed	CMJ height ↓ 3.4% after 60s; peak power ↓ 2.0%; avg power ↓ 2.7%; no change after 30s	Duration threshold: ≥60s impairs SSC performance; ≤30s negligible	60s static stretching impaired jump height and power; 30s had no effect	Small sample; only men; immediate effects only; no warm-up included
Ryan et al.	2010	Randomised repeated-measures design, 3 conditions	n = 30 (15M, 15F)	Healthy adults, mean age 25 yrs	CRAC stretching with warm-up (WS), CRAC stretching only (SO), control (CON)	Hamstrings, hip flexors, plantar flexors, quadriceps	Passive stretch → 7s isometric contraction → 4s antagonist contraction; repeated 3–4 times	ROM measured but not primary outcome	Not assessed	Not assessed	Warm-up inclusion vs. no warm-up; balance indices (A/P, M/L)	CRAC stretching improved medial-lateral stability vs. control, both with and without warm-up	Small sample, healthy young adults only, immediate effects
McMillian et al.	2006	Randomised crossover, 3 conditions	n = 30 (16M, 14F)	US Military Academy cadets, ages 18–24	Dynamic warm-up (DWU), Static warm-up (SWU), No warm-up (NWU)	Whole-body calisthenics and stretches	DWU: progressive calisthenics + movement drills; SWU: static stretches; each 10 min	Not assessed	DWU significantly improved T-drill agility vs. SWU & NWU	DWU improved medicine ball throw and 5-step jump; SWU only improved 5-step jump vs. NWU	Warm-up type; gender had no effect	DWU enhanced agility and power across all tests; SWU neutral except slight benefit in 5-step jump	Small sample, only cadets, immediate effects



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