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REVIEW ARTICLE

Acute Effects of Dynamic Stretching on Muscle Flexibility and Performance: An Analysis of the Current Literature

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Abstract Stretching has long been used in many physical activities to increase range of motion (ROM) around a joint. Stretching also has other acute effects on the neuromuscular system. For instance, significant reductions in maximal voluntary strength, muscle power or evoked contractile properties have been recorded immediately after a single bout of static stretching, raising interest in other stretching modalities. Thus, the effects of dynamic stretching on subsequent muscular performance have been questioned. This review aimed to investigate performance and physiological alterations following dynamic stretching. There is a substantial amount of evidence pointing out the positive effects on ROM and subsequent performance (force, power, sprint and jump). The larger ROM would be mainly attributable to reduced stiffness of the muscle–tendon unit, while the improved muscular performance to temperature and potentiation-related mechanisms caused by the voluntary contraction associated with dynamic stretching. Therefore, if the goal of a warm-up is to increase joint ROM and to enhance muscle force and/or power, dynamic stretching seems to be a suitable alternative to static stretching. Nevertheless, numerous studies reporting no alteration or even performance impairment have highlighted possible mitigating factors (such as stretch duration, amplitude or velocity). Accordingly, ballistic stretching, a form of dynamic stretching with greater velocities, would be less beneficial than controlled dynamic stretching. Notwithstanding, the literature shows that inconsistent description of stretch procedures has been an important deterrent to reaching a clear consensus. In this review, we highlight the need for future studies reporting homogeneous, clearly described stretching protocols, and propose a clarified stretching terminology and methodology.

Abbreviations

BS	Ballistic stretching
CMJ	Countermovement jump
DE	Dynamic exercise
DJ	Drop jump
DS	Dynamic stretching
DWU	Dynamic warm-up
EMG	Electromyography
FDE	Fast dynamic exercise
ISOK	Isokinetic dynamometer
MTU	Muscle–tendon unit
NS	No stretching
PAP	Post-activation potentiation
PNF	Proprioceptive neuromuscular facilitation
PT	Peak torque
RM	Repetition maximum
ROM	Range of motion
RSA	Repeated sprint ability
SDE	Slow dynamic exercise
SS	Static stretching

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Key Points

Acute effects of dynamic stretching on flexibility and muscular performance have been widely studied, but there is little knowledge regarding the underlying mechanisms.

Despite inconsistent description of stretch procedures in the literature, dynamic stretching seems to be a suitable alternative to static stretching as part of a warm-up.

Future studies should use common terminology and methodological rules to reach a clear consensus on the effects induced by dynamic stretching.

1 Introduction

Warm-up prior to an athletic event is considered essential to optimise performance [1]. Traditionally, it is composed of different activities including a bout of static stretching [2]. This usually involves moving a limb to its end range of motion (ROM) and holding this stretched position for several seconds [2]. Static stretching has largely been demonstrated to be an effective method to increase ROM around a joint [2–5]. The so-defined increased flexibility has primarily been attributed to decreased stiffness of the muscle–tendon unit (MTU) [6–8] as well as increased tolerance to stretch [9]. Nevertheless, studies have often demonstrated that this stretching modality could induce acute detrimental effects. Significant reductions in maximal voluntary strength, muscle power or evoked contractile properties (here called muscular performance) were recorded immediately after a single bout of static stretching [5, 8, 10–29]. They could originate from various neural and peripheral mechanisms, and more particularly from musculotendinous stiffness reductions [8, 16, 30–37]. Thus, the literature asserts that static stretching should be used carefully, or even avoided during warm-up to prevent subsequent potentially deleterious effects on muscular performance. Interest has also focused on the effect of other stretching modalities such as dynamic stretching.

Recent studies have found a considerable amount of evidence showing that an acute bout of dynamic stretching can enhance ROM about a joint, leading to recommendations for dynamic stretching as a pre-performance routine rather than static stretching [4, 38–52]. Among these studies, some have indicated that dynamic stretching provides similar or greater acute increases in flexibility than static stretching [4, 40, 45, 46, 48, 49]. Moreover, numerous studies have demonstrated an acute increase in power, sprint or jump performance after dynamic stretches [4, 39, 51–62]. This stretch modality has been shown to be more efficient than no-stretch [45, 56, 59, 60, 63–72] and than static stretching for muscular performance [45, 51, 56, 63, 66–88]. Nevertheless, there are also reports in the literature about impaired performance following dynamic stretching [41, 42, 47, 57, 86, 89, 90]. It appeared that the magnitude of the stretch-induced effects could be attributed to several factors such as muscle group, stretching duration, stretching intensity or contraction type and velocity [12, 91]. While static stretch-induced effects on muscular performance and their underlying mechanisms have been rigorously studied, results are still unclear for dynamic stretching. Indeed, the reasons behind muscular performance improvements after dynamic stretching still need to be elucidated. Voluntary contractions are often put forward as contributive, but methodological difficulties and terminological issues remain a problem.

In the literature, studies dealing with dynamic stretching effects on performance do not provide a clear consensus. Authors use a variety of terms describing many different stretching designs (e.g. dynamic, ballistic, applied on single or multiple joints while walking, moving or staying stationary, etc.). Moreover, the literature is often inconsistent in the description of stretch procedures. For instance, dynamic stretching is often confused with ballistic stretching. Both stretching methods consist of performing movements through the full ROM by contracting agonist muscles, which allows the antagonist muscle group to elongate, without a held end position. However, dynamic stretching is performed in a controlled manner, whilst ballistic stretching is a rapid and uncontrolled movement that could include bouncing (Table 1). Despite this difference, Carvalho et al. [79] used the term 'dynamic' for their protocol during which subjects were instructed to bob (referring to a bouncing movement) joints in 1:1-s cycles, yet Bacurau et al. [38] referred to this same stretch procedure as 'ballistic'. Elsewhere, dynamic and ballistic stretching findings are often pooled to examine their effects on muscular performance (especially Behm and Chaouachi [12]). However, if the two stretching protocols are considered separately, the effect on subsequent performance is not the same. Indeed, throughout the literature, studies considering ballistic stretching generally report neutral or negative effects on performance [47, 79, 86, 88, 92], whilst dynamic stretching studies show neutral or positive effects [53, 54, 56, 57]. Accordingly, ballistic stretches are recommended less because they are less beneficial due to the greater tension created within the muscle [93]. Ballistic stretching could create uncontrolled forces exceeding muscle extensibility [94].

Table 1 Examples of descriptive characteristics of dynamic and ballistic stretching

References	Dynamic	Ballistic
[43]	(…) through range of motion by contracting the agonist muscles, which allows the antagonist muscles to relax and elongate (…)	
[93]	(…) through the full ROM at a controlled, slow tempo. All movements are performed slowly and deliberately	(…) is a bouncing, rhythmic motion and uses the momentum of a swinging body segment to vigorously lengthen the muscle
[94]		(…) is usually associated with bobbing, bouncing, rebounding, and rhythmic motion. It imposes passive momentum that exceeds static ROM (…)
[95]	(…) is the act of moving a joint through its entire range of motion in a quick manner with little resistance	(…) is a rapid, bouncing movement (…) through the range of motion until the muscles are stretched to their limits. (…) is performed at high speeds, making it difficult to control the rate and degree of stretch as well as the amount of force being applied
[96]		(…) involves repetitive bouncing movements in the muscle's lengthened position
[97]	(…) by contracting antagonist muscle group(s) of target muscle group(s) without bouncing (…)	

ROM range of motion

To make sound recommendations about the use of dynamic stretching as a possible alternative to static stretching in warm-up, this review attempts to investigate negative, null and positive muscular performance responses to dynamic stretching and provide some clarity regarding conflicting findings. A distinction between dynamic and ballistic stretching will be made in order to establish a clear consensus about their effects on subsequent muscular performance and underlying mechanisms. Also, we will try to come up with a consensus of definitions that researchers can use.

2 Materials and Methods

2.1 Search Strategy

This review integrated studies that examined the acute effects of dynamic stretching on subsequent flexibility and muscular performance. An electronic literature search was performed independently by the two authors using the PubMed database. The following terms were used in 'all fields' (dynamic stretching OR ballistic stretching OR dynamic warm-up) while the terms, patient, injury, disease and animal were excluded (using NOT). Figure 1 shows a flowchart illustrating the search strategy. Articles were screened first by title and by abstract using the inclusion criteria described below. Then, the full text was retrieved for all potentially relevant full-text articles and assessed for eligibility. Additional manual searches, including reference lists of selected studies were performed using PubMed, ResearchGate, ScienceDirect and Google Scholar databases. The search ended on 2 March 2017.

2.2 Study Selection and Inclusion Criteria

To examine the effects of an acute dynamic and ballistic stretch intervention on subsequent muscular performance and the stretch-related neural and peripheral mechanisms, the following inclusion criteria were used: (1) studies must have been written in English and published as an article in a peer-reviewed journal or conference proceeding; (2) studies must concern healthy and active human subjects without any musculoskeletal disease; (3) studies must compare at least two acute interventions (intervention-based studies examining pre- and post-stretch data were also included), (4) in a random order; (5) results must include functional performance (e.g. vertical jump, sprint, agility, running economy, activity specific movement and others), biomechanical (e.g. ROM, torque, muscular contractile properties, stiffness and others) and/or physiological [e.g. electromyography (EMG) activity, temperature, muscular reflex activity and others] measures. Studies were excluded according to the following criteria: (1) interventions were not applied in a random order; (2) results were not compared with pre-data of dynamic stretching, static stretching or no-stretching condition; (3) results did not include functional performance or biomechanical or physiological measures.

Effect size, which is a standardised value that permits the determination of the magnitude of the differences between groups or experimental conditions [98], was calculated for each study that provided absolute mean data and standard deviations. Cohen assigned descriptors to the effect sizes such that effect sizes less than 0.4 represented a small magnitude of change while 0.41–0.7 and > 0.7

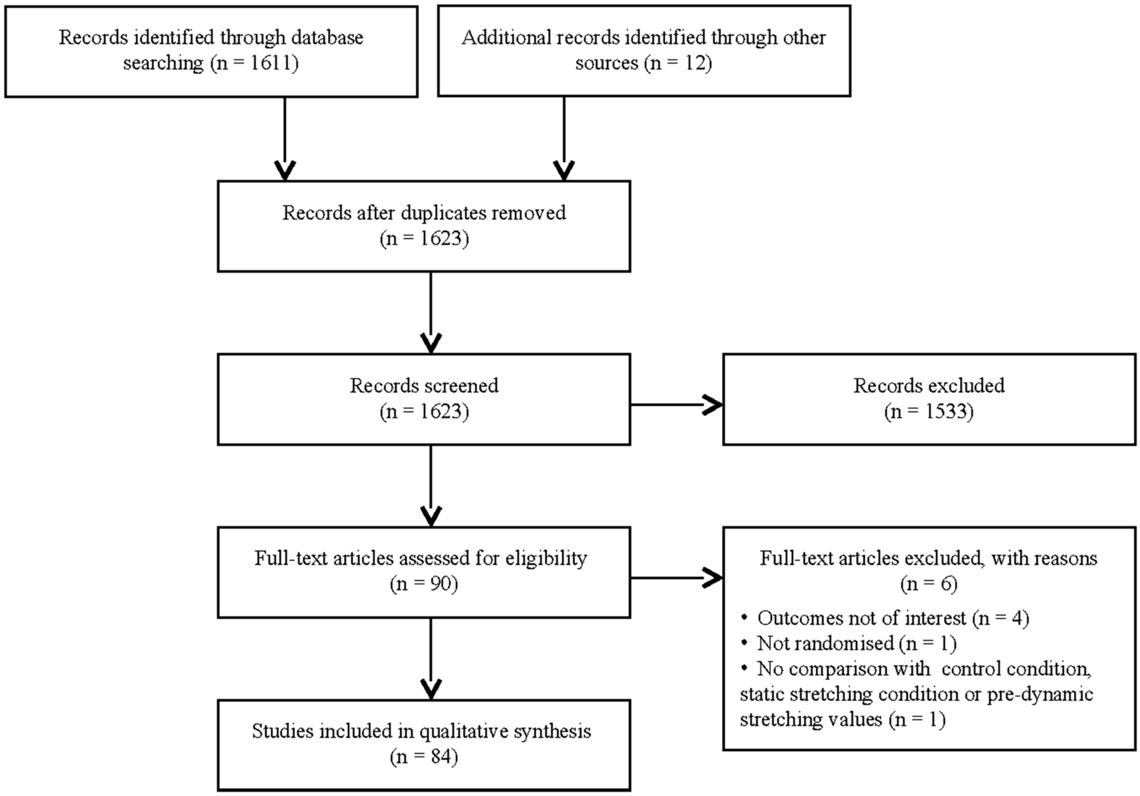

Fig. 1 Flowchart illustrating the search strategy

represented moderate and large magnitudes of change, respectively.

3 Acute Effects of Dynamic Stretching

The increase of joint ROM is a main goal of stretching in sports medicine and exercise. There is considerable evidence that an acute bout of dynamic stretching can enhance ROM around a joint [4, 38–48, 50–52, 68, 80, 99–103] (Table 2). Some studies showed that dynamic stretching provided a similar or greater acute increase in flexibility compared with static stretching [4, 40, 45, 46, 48, 49, 68, 99, 100, 102, 103]. On the other hand, others showed that static stretch was more efficient than dynamic stretch for ROM improvements [38, 42, 44, 80, 104]. These conflicting results could be ascribed to the different natures of stretching, which that renders comparisons difficult. Indeed, as compared with static stretching, less time is spent in a lengthened position during dynamic stretching. The viscoelastic stress relaxation that occurs when the muscle tissue is kept stretched in a fixed position during static stretching [105, 106] may be a factor in the difference in stretch-induced effects on flexibility. It seems to be attributable to increased tendon elasticity and decreased muscle viscosity, which produce decreased passive torque and increased ROM [107]. In contrast, because muscles are contracting actively and repeatedly to stretch muscles, dynamic stretching may help in the warm-up process by increasing muscle temperature [54, 56, 108, 109]. It has been proposed that an increase in temperature may decrease the viscous resistance of muscles [110] and by consequence enhance tissue extensibility. Moreover, the greater angular displacement during dynamic stretching could contribute to the possible greater ROM enhancement as compared with the ROM certain authors have observed with static stretching [40]. Again, the distinction between dynamic and ballistic stretching must be made. Indeed, it has been reported that ballistic stretching, involving an uncontrolled and bouncing movement, may cause facilitation of the stretch reflex and thus induce contraction in the stretched muscle. As a consequence, ballistic stretching may be disadvantageous for improving ROM [111, 112]. Further studies are needed to explain these conflicting findings and to determine whether the use of dynamic rather than static or ballistic stretching for the warm-up would tend to be more appropriate to enhance flexibility.

In contrast to static stretching, dynamic stretching is nowadays recommended as a pre-performance routine because of the demonstrated acute increase in power, sprint or jump performance [4, 39, 51–62]. Dynamic stretching

Table 2 Acute effects of dynamic and ballistic stretching on subsequent muscular performance

References	*n*	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	*P* value
Aguilar et al. [102]	45	Quadriceps, hamstrings, hip extensors, hip flexors, hip adductors, hip abductors, plantar flexors	DWU	< ROM	10 yard (5 reps) × 20 exercises	NR	Hamstring flexibility	+ 35.98%	0.71	< 0.0001
							Quadriceps flexibility	+ 0.55%	0.08	> 0.05
							Hip flexor flexibility	+ 6.95%	0.27	> 0.05
							Rectus femoris flexibility	+ 4.57%	0.25	> 0.05
							Eccentric quadriceps PT	+ 10.43%	0.39	0.012
							Concentric quadriceps PT	No change: + 6.48%	0.38	> 0.05
							Eccentric hamstrings PT	No change: + 3.1%	0.19	> 0.05
							Concentric hamstrings PT	No change: + 6.72%	0.36	> 0.05
							Vertical jump height	No change: + 6.64%	0.1	> 0.05
							Vertical jump power	No change: + 1.82%	0.06	> 0.05
Alemdaroglu et al. [88]	12	Quadriceps, hamstrings, gluteals, plantar flexors	BS	ROM	30-s × 4 sets × 5 stretches	1:1-s	10-m sprint time	+ 1.08%	0.29	< 0.05
							20-m sprint time	+ 0.6%	0.1	< 0.05
Amiri-Khorasani et al. [40]	18	Quadriceps, hamstrings, gluteals, adductors, gastrocnemius	DS	ROM	15-s × 5 stretches	1:1-s	Total dynamic ROM	DS > NS: NR	NR	< 0.01
Amiri-Khorasani et al. [83]	20	Quadriceps, hamstrings, hip extensors, hip flexors, hip adductors, gastrocnemius	DS	ROM	15 reps × 6 stretches	1:1-s	Acceleration time (10 m)	DS < SS: NR	NR	< 0.053
						5 × slow, 5 × moderate and 5 × as quickly as possible	Speed time (20 m)	DS < SS: NR	NR	< 0.037

Table 2 continued

References	*n*	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	*P* value
Ayala et al. [119]	49	Quadriceps, hamstrings, gluteus, psoas, adductors	DS	ROM	15-reps × 2 sets × 5 stretches	1:1-s	Eccentric knee flexors PT	1.04 rad/s: DS (+ 2.6%) = NS	0.11	> 0.05
						Controlled speed		3.14 rad/s: DS (− 0.5%) = NS	0.05	> 0.05
							Eccentric knee flexors work	1.04 rad/s: DS (+ 3.2%) = NS	0.11	> 0.05
								3.14 rad/s: DS (+ 4.4%) = NS	0.17	> 0.05
Ayala et al. [87]	12	Quadriceps, hamstrings, hip extensors, hip flexors, hip adductors, hip abductors, plantar flexors	DE	ROM	3 sets × 6 exercises (6-8-min)	Controlled manner	CMJ height	DE > SS: + 2.8%	0.35	< 0.05
						Low to high intensity	20-m sprint time	DE < SS: − 3.9%	1.06	< 0.05
							Serve speed	DE < SS: + 4.0%	1.03	< 0.05
							Serve accuracy	DE > SS: + 11.0%	0.83	< 0.05
Bacurau et al. [38]	14	Quadriceps, hamstrings	BS	NA	30-s × 3 sets × 6 stretches (20-min)	1:1-s	1RM	No change: − 2.2%	NR	> 0.05
							Hip joint ROM	+ 9.4%	0.97	< 0.001
							Hamstring flexibility	+ 8.91%	0.62	< 0.001
Barroso et al. [101]	12	Quadriceps, hamstrings, gluteus maximum	BS	NR	30-s × 3 sets × 3 stretches	1:1-s	Hamstrings flexibility	+ 2.9%	NR	< 0.05
							Leg-press 1RM	BS (− 2.39%) = NS	0.14	< 0.05
							Number of repetitions (80% 1RM)	BS (− 17.78%) < NS	1.4	0.001
							Total volume (80% 1RM)	BS (− 17.93%) < NS	0.79	< 0.001
Beedle et al. [124]	51	Chest, shoulder, triceps, quadriceps, hamstrings	DS	ROM	15 reps (30-s) × 3 sets × 2 stretches	1:1-s	Bench press 1RM	DS = NS: − 0.66%	NR	> 0.05
							Leg press 1RM	DS = NS: + 0.48%	NR	> 0.05
Behm et al. [100]	10	Quadriceps, hamstrings, plantar flexors	DE	ROM	30-s (8 rep) × 3 exercises	NR	Hamstrings flexibility	+ 5.7%	NR	0.004
							CMJ height	DE > NS: + 7.9%	NR	< 0.0001
Bradley et al. [113]	18	Quadriceps, hamstrings, plantar flexors	BS (passively)	ROM	30-s × 4 sets × 5 stretches (10-min)	1:1-s	Vertical jump height	No change: − 2.7%	NR	> 0.05

Table 2 continued

References	n	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	P value
Byrne et al. [59]	29	Quadriceps, hamstrings, hip flexors, hip extensors, adductors	DE	NR	30-s × 10 exercises	NR	20-m sprint time	DE < NS: − 2.2%	0.66	0.001
Carvalho et al. [79]	16	Quadriceps, hamstrings, triceps surae	DS	ROM	30-s × 3 sets × 3 stretches (5-min)	1:1-s	CMJ height	DS = NS: NR	NR	> 0.05
							SJ height	DS = NS: NR	NR	> 0.05
Chatzopoulos et al. [65]	31	Front deltoid, side deltoid, pectoral, triceps, back, quadriceps, hamstrings, adductors, calves	DE	NR	18-m × 8 exercises (7-min)	NR	Balance (s)	DE > NS: + 12.3%	0.4	< 0.05
							Agility time	DE > NS: + 3.54%	0.54	< 0.05
							Movement time	DE > NS: + 5.97%	0.46	< 0.05
							Reaction time	DE (− 0.53%) = NS	0.03	> 0.05
Chatzopoulos et al. [122]	27	Deltoid, pectoral, triceps, quandriceps, hamstrings, adductors, gastrocnemius	DE	NR	18-m × 7 exercises (5-min)	NR	Reaction time	DE = NS: 0%	0.0	> 0.05
							Movement time	DE = NS: − 2.73%	0.18	> 0.05
							Change of direction speed	DE = NS: 0%	0.0	> 0.05
Christensen et al. [115]	68	Quadriceps, hamstrings, hip adductors, calves	DE	NR	5 reps × 2 sets × 8 exercises	NR	CMJ height	DE (+ 0.1%) = NS	NR	> 0.05
Clark et al. [121]	21	Calves	DS	NR	20-m × 3 sets	NR	CMJ peak power	No changes: NR	NR	0.424
Costa et al. [89]	21	Quadriceps, hamstrings	DS	NR	30-s × 4 sets × 4 stretches (16.1 ± 2.6-min)	Controlled movement	Concentric quadriceps PT	60°/s: No change: − 1.64%	0.06	> 0.05
									0.02	> 0.05
							Concentric hamstrings PT	180°/s: No change: − 0.54%	0.44	< 0.05
									0.48	< 0.05
							Eccentric hamstrings PT	60°/s: − 10.0%	0.69	< 0.05
								180°/s: − 10.6%	0.67	< 0.05
								60°/s: − 16.04%		
								180°/s: −13.7%		
Curry et al. [46]	24	Quadriceps, hamstrings, gluteals, hip flexors, adductors, gastrocnemius, soleus	DE	ROM	10 reps × 2 sets × 9 exercises (10-min)	Controlled movement	ROM quadriceps	+ 6.03%	0.46	< 0.05
							CMJ height	No change: + 1.89%	0.13	> 0.05
							Time to peak force	No change: 27.27%	0.59	> 0.05

Table 2 continued

References	*n*	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	*P* value
Dalrymple et al. [117]	12	Quadriceps, hamstrings, hip extensors, plantar flexors	DE	ROM	18-m × 2 sets × 4 exercises	NR	Vertical jump height	DE = NS: NR	NR	> 0.05
Duncan and Woodfield [68]	50	Quadriceps, hamstrings, hip extensors, hip flexors, adductors	DE	NR	18-m × 2 sets × 8 exercises (10-min)	Low to moderate intensity	CMJ height Hamstrings flexibility	DE > NS: + 2.82% DE (+ 2.07%) = NS	0.2 0.08	< 0.05 > 0.05
Fattahi-Bafgui and Amiri-Khorasani [85]	20	Quadriceps, hamstrings, gluteals, hip flexors, adductors, gastrocnemius	DS DE	ROM	15 reps × 6 stretches 10-m × 6 exercises	1:1-s 5 × slow, 5 × moderate and 5 × as quickly as possible	Vertical jump height	DS > SS: NR DE = DS and SS: NR	NR NR	< 0.002 > 0.05
Fattahi-Bafgui and Amiri-Khorasani [70]	15	Quadriceps, hamstrings, gluteals, hip flexors, adductors, gastrocnemius	DS	ROM	15 reps × 6 stretches	1:1-s 5 × slow, 5 × moderate and 5 × as quickly as possible	Height jump Agility time	DS > NS: + 2.52% DS < NS: − 1.71%	0.28 0.39	< 0.05 < 0.05
Fletcher and Jones [55]	97	Quadriceps, hamstrings, gluteals, hip flexors, adductors, gastrocnemiis, solei	DS DE	ROM	20 reps × 5 stretches 20 reps × 5 exercises	Controlled movement	20-m sprint time	DS: No change: − 0.92% DE: − 1.85%	0.14 0.31	> 0.05 < 0.05
Fletcher and Monte-Colombo [72]	27	Quadriceps, hamstrings, gluteus maximus, hip flexors, adductors, abductors, gastrocnemius, solei	DE	< ROM	12 reps × 2 sets × 8 exercises	NR	CMJ height 20-m sprint time Balsom agility (s)	DE = NS: + 1.89% DE < NS: − 2.99% DE < NS: − 2.5%	0.19 0.69 0.59	> 0.05 < 0.05 < 0.05
Fletcher [54]	24	Quadriceps, hamstrings, hip extensors, hip flexors, adductors, plantar flexors	DE	NR	10 reps × 2 sets × 5 exercises	SDE: 50 beats/min FDE: 100 beats/min	SJ height CMJ height DJ height	SDE: No change: + 0.21% FDE: + 3.15% SDE: No change: − 0.21% FDE: + 4.17% SDE: No change: + 0.61% FDE: + 6.17%	0.01 0.17 0.01 0.24 0.04 0.37	> 0.05 < 0.05 > 0.05 < 0.05 > 0.05 < 0.05

Table 2 continued

References	n	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	P value
Franco et al. [84]	15	Quadriceps, hamstrings, calves	DS	NR	15 reps × 3 sets × 3 stretches	5 × slowly and 10 × as fast as possible	Mean power (Wingate)	DS = NS: NR	NR	> 0.05
							Time to peak power (Wingate)	DS > NS: NR	NR	< 0.001
							Peak power (Wingate)	DS = NS: NR	NR	> 0.05
Gelen et al. [64]	26	Quadriceps, hamstrings, hip rotators, adductors, calves	DE	NR	15-m × 12 exercises (10-min)	In rhythm, slowly or as fast as possible	30-m sprint time	DE < NS: − 4.1%	0.95	< 0.03
							Slalom dribbling time	DE < NS: − 5.1%	1.20	< 0.01
							Penalty kick speed	DE > NS: + 3.3%	1.25	< 0.03
Haddad et al. [67]	16	Quadriceps, hamstrings,hip flexors, adductors, plantar flexors	DS	NR	30-s × 2 sets × 5 stretches	NR	5 jump test	DS > NS: + 1.6%	0.4	0.000
							10-m sprint time	DS < NS: − 2.1%	0.76	0.000
							20-m sprint time	DS < NS: − 1.0%	0.55	0.000
							30-m sprint time	DS < NS: − 1.1%	0.7	0.000
							RSA (s)	DS (−0.22%) = NS	0.11	> 0.05
Hayes and Walker [103]	7	Quadriceps, hamstrings, gluteals, hip flexors, calves	DS	ROM	30-s × 5 stretches	Controlled velocity	Hamstring flexibility	+: NR	NR	< 0.05
							Running economy	DS = NS: NR	NR	> 0.05
Herda et al. [109]	14	Hamstrings	DS	NR	30-s × 4 sets × 3 stretches (9.1 ± 0.3 min)	Slow and controlled manner	PT	No change: NR	NR	> 0.05
Herda et al. [41]	14	Hamstrings	DS (ISOK)	ROM	30-s × 4 sets	Self-selected pace	PT (65°)	− 9.67%	0.32	0.007
							PT (80°)	+ 13.34%	0.47	0.003
							Passive ROM	+: NR	NR	0.003
Hough et al. [53]	11	Quadriceps, hamstrings, hip extensors, hip flexors, plantar flexors	DS	NR	30-s × 5 stretches (7-min)	1:1-s 5 × slowly and 10 × as quickly as possible	CMJ height	+ 4.9%	NR	< 0.05

Table 2 continued

References	n	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	P value
Jaggers et al. [95]	10	Quadriceps, hamstrings, spinal erectors, sartorius, hip flexors, hip extensors, hip adductors, gastrocnemius	BS	ROM	15 reps × 2 sets × 5 stretches	126 beats/min	CMJ height	BS (+ 3.04%) = NS	0.16	0.37
			DE		30-s × 2 sets × 5 exercises	5 × slowly and 10 × as quickly as possible		DE (+ 7.03%) = NS	0.36	0.13
							Maximal power	BS (+ 3.33%) = NS	0.15	0.56
								DE (+ 4.04%) = NS	0.18	0.07
							Maximal force	BS (+ 2.25%) = NS	0.07	0.77
								DE (+ 9.38%) = NS	0.3	0.52
Kendall [120]	10	Quadriceps, hamstrings, hip extensors, hip flexors, hip adductors, hip abductors, plantar flexors	DE	NR	20-m × 11 exercises	NR	Wingate anaerobic peak power	DE = NS: + 6.45%	0.37	NR
							Mean anaerobic power	DE = NS: NR	NR	0.08
							Power drop	DE = NS: NR	NR	0.07
							Fatigue index	DE = NS: NR	NR	0.53
Konrad et al. [49]	24	Plantar flexors	BS (ISOK)	ROM	30-s × 4 sets	1:1-s	ROM	+ 4.36%	0.25	0.04
							Passive resistive torque	− 11.56	0.37	0.00
Kruse et al. [60]	11	Quadriceps, hamstrings, hip extensors, hip flexors, adductors, abductors, obliques, plantar flexors	DE	NR	30-s (20 m) × 14 exercises (7-min)	NR	CMJ height	DE > NS: +6.75	1.15	0.001
Leone et al. [61]	30	Pectoralis major, triceps brachii	DS	ROM	10 reps × 3-s × 2 stretches	Controlled slow-moderate	Bench press maximal isometric peak force	+ 3.6%	0.19	< 0.05
							Bench press time to maximal isometric force	No change: + 4.69%	0.14	> 0.05
							Bench press rate of force production	No change: + 6.86%	0.2	> 0.05

Table 2 continued

References	n	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	P value
Little and William [63]	18	Quadriceps, hamstrings, gluteals, hip flexors, adductors, gastrocnemius	DE	ROM	30-s × 5 exercises (6.2-min)	1:1-s	Vertical jump height	DE = NS: NR	NR	0.074
							Agility time	DE > NS: NR	NR	0.001
							10 m acceleration time	DE < NS: NR	NR	0.011
							20 m velocity	DE > NS: NR	NR	< 0.0005
Manoel et al. [74]	12	Quadriceps	DS	NR	30-s × 3 sets	As quick as possible	Knee extension power (60°/s)	+ 8.9%	1.51	< 0.05
							Knee extension power (180°/s)	+ 6.3%	1.05	< 0.05
McMillian et al. [66]	30	Trunk flexors/extensors, back and abdominal muscles, quadriceps, hamstrings, hip posteriors, calves,	DWU	NR	10 reps or 20–25-m × 15 exercises	Slow to moderate cadence	T-drill run time	DWU < NS: -2.15%	0.26	< 0.01
							Medicine ball throw	DWU > NS: +3.27%	0.11	< 0.01
							5-step jump	DWU > NS: + 5.47%	0.46	< 0.01
Mizuno et al. [128]	12	Medial gastrocnemius	DS (ISOK)	NR	30-s (15 reps) × 4 sets	60 batt/min	ROM	+ 21.6%	1.77	0.005
							PT (end of ROM)	DS > NS: NR	NR	0.032
							PT (during the final 13° of ROM)	DS > NS: NR	NR	0.042
Mizuno et al. [52]	15	Plantar flexors	DS (ISOK)	ROM	DS1: 15 reps (30-s) × 1 set	60 batt/min	ROM	DS1: No change: NR	NR	0.442
					DS4: 15 reps (30-s) × 4 sets			DS4: +: NR	NR	0.007
					DS7: 15 reps (30-s) × 7 sets			DS7: +: NR	NR	0.002
							End ROM passive torque	DS1: No change: NR	NR	> 0.05
								DS4: No change: NR	NR	> 0.05
								DS7: No change: NR	NR	> 0.05
Morrin et al. [80]	10	Quadriceps, hamstrings, gluteus maximus, gastrocnemius	DS		60-s × 3 stretches	1:1-s	Hamstrings ROM	DS < NS: NR	NR	> 0.05
						Moderate intensity pace	Vertical jump height	DS (+ 8.86%) = NS	0.81	> 0.05
							Balance (cm^2)	DS (− 33.63%) = NS	0.62	> 0.05

Table 2 continued

References	*n*	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	*P* value
Murphy et al. [99]	42	Pectoralis major, deltoids, latissimus dorsi, hamstrings, quadriceps, gluteus maximus, hip flexors, calves	DS	< ROM	10 reps (20-s) × 12 stretches	1:1-s 5 × Slowly and 10 x as quickly as possible	Vertical jump height	No change: + 1.96%	0.14	> 0.017
							ROM hip	No change: + 5.67%	0.42	> 0.017
							ROM knee	No change: + 0.19%	0.04	> 0.017
							Hamstrings flexibility	+ 7.72%	0.18	0.011
Needham et al. [81]	22	Quadriceps, hamstrings, gluteals, hip flexors, adductors, gastrocnemius	DE	NR	18-m × 2 sets × 6 exercises	Moderate to high intensity	Vertical jump height	DE > SS: + 4.44%	NR	< 0.05
							10-m sprint time	DE < SS: − 2.2%	NR	< 0.05
							20-m sprint time	DE < SS: − 1.0%	NR	< 0.05
Nelson and Kokkonen [47]	22	Quadriceps, hamstrings, gluteals, adductors, plantar flexors	BS	ROM	15-s × 3 sets unassisted × 5 stretches 15-s × 3 sets assisted × 5 stretches	1:1-s	Hamstrings flexibility	+ 8.3%	3.17	< 0.05
							Knee-flexion 1RM	BS < NS: − 7.23%	1.13	< 0.05
							Knee-extension 1RM	BS < NS: − 5.23%	0.81	< 0.05
Pagaduan et al. [118]	29	Quadriceps, hamstrings, hip extensors, hip flexors, adductors, abductors, obliques, plantar flexors	DE	NR	20-s × 2 sets × 7 exercises (7-min)	NR	CMJ height	DE (+ 2.81) = NS	0.24	> 0.05
Pappas et al. [62]	14	Quadriceps, hamstrings, hip extensors, plantar flexors	DS	NR	80-s × 4 stretches (6-min)	1:1-s	Vertical ground reaction force	+ 1.7%	0.14	< 0.05
							Fligth time	+ 5.8%	0.3	< 0.05
							Step length	+ 2.2%	0.33	< 0.05
							Contact time	No change: + 0.33%	0.0	> 0.05
Paradisis et al. [42]	48	Quadriceps, hamstrings, hip extensors, plantar flexors	DS	NR	40-s × 4 stretches	1:1-s	20-m sprint time	+ 0.8%	0.1	< 0.05
							CMJ height	− 2.2%	0.1	< 0.05
							Hamstrings flexibility	+ 6.5%	0.14	< 0.05
Pearce et al. [73]	13	Quadriceps, hamstrings, hip extensors, hip flexors, adductors, plantar flexors	DE	ROM	10 reps or 10-m × 1–2 sets × 7 exercises	NR	Vertical jump height	No change: + 3%	NR	0.25
							Vertical jump peak power	No change: + 0.7%	NR	0.32

Table 2 continued

References	n	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	P value
Perrier et al. [45]	21	Quadriceps, hamstrings, gluteals, hip flexors, adductors, piriformis, gluteal, obliques, calves	DWU	NR	18.3-m × 2 × 11 exercises (9.1 ± 0.3 min)	Increasing intensity (mean = 5.2 ± 1.2 on the Borg CR10 scale)	CMJ height	DWU > NS: + 3.72%	0.24	0.005
							Hamstrings flexibility	DWU > NS: + 9.64%	0.41	< 0.001
							Reaction time	DWU (− 0.98%) = NS	0.08	0.08
Ryan et al. [39]	26	Quadriceps, hamstrings, hip extensors, hip flexors, hip adductors, abductors, plantar flexors	DE	ROM	DE1: 11 exercises (6-min) DE2: 2 sets × 11 exercises (12-min)	Controlled movement Low, moderate and high intensity	CMJ height	DE1: + 6.2%	0.41	< 0.001
								DE2: + 5,6%	0.37	< 0.001
							CMJ velocity	DE1: + 6,1%	0.58	< 0.001
								DE2: + 4,8%	0.45	< 0.001
							Hamstring flexibility	DE1: + 10.7%	0.4	< 0.001
								DE2: + 8.2%	0.35	< 0.001
							Muscular endurance	DE1 = NS: NR	NR	> 0.05
								DE2 < NS: -15.6%	NR	0.01
Sá et al. [86]	9	Knee extensors, knee flexors, hip adductors, plantar flexors	BS	NR	1-min × 3 sets × 4 stretches	1:1-s	Total number of reps leg press	BS < NS: − 14.11%	NR	0.014
							Total number of reps leg curl	BS < NS: − 20.97	NR	0.002
							Total number of reps in session	BS < NS: − 10.19	NR	0.002
Samuel et al. [90]	24	Quadriceps, hamstrings	BS	ROM	30-s × 3 sets × 2 stretches	60 batt/min	Vertical jump height	BS = NS: NR	NR	> 0.05
							Vertical jump power	BS < NS: − 2.4%	NR	< 0.05
							Quadriceps torque	BS = NS: NR	NR	> 0.05
							Hamstrings torque	BS = NS: NR	NR	> 0.05
Samukawa et al. [43]	20	Plantar flexors	DS	NR	30-reps × 5 sets	1:1-s	ROM	+ 32.16%	0.78	< 0.0001

Table 2 continued

References	*n*	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	*P* value
Sekir et al. [58]	10	Quadriceps, hamstrings	DS	ROM	15-reps × 2 sets × 4 stretches (6 ± 1 min)	1:1-s 5 × slowly and 10 × as quickly as possible	Concentric quadriceps PT	60°/s: + 8.41% 180°/s: + 11.81%	1.12 1.5	< 0.001 < 0.01
							Eccentric quadriceps PT	60°/s: + 14.5% 180°/s: + 15.04%	1.95 2.11	< 0.001 < 0.001
							Concentric hamstrings PT	60°/s: + 6.8% 180°/s: No change: + 6.42%	1.11 1.07	< 0.05 < 0.05
							Eccentric hamstrings PT	60°/s: + 14.11% 180°/s: + 14.47%	1.7 1.58	< 0.001 < 0.001
Siatras et al. [116]	11	Quadriceps, hamstrings, calves, tibialis anterior	DS	ROM	30-s × 2 stretches	As fast as possible	0–15-m speed vaulting	DS = NS: NR	NR	> 0.05
							0–5-m speed vaulting	DS = NS: NR	NR	> 0.05
							5–10-m speed vaulting	DS = NS: NR	NR	> 0.05
							10–15-m speed vaulting	DS = NS: NR	NR	> 0.05
Su et al. [51]	30	Quadriceps, hamstrings	DE	ROM	15 reps (30-s) × 3 sets × 2 exercises	Controlled movement	Quadriceps flexibility	+ 2.22%	0.46	< 0.05
							Hamstring flexibility	+ 5.91%	1.10	< 0.05
							Knee extension peak torque	+ 4.51%	0.45	< 0.05
							Knee flexion peak torque	No change: + 1.37%	0.14	> 0.05
Taylor et al. [82]	13	Quadriceps, hamstrings, hip extensors, hip flexors, adductors, abductors, obliques, plantar flexors	DWU	ROM	5–10 reps or 10–30-m × 16 exercises	Gradually progressing in intensity	Vertical jump height	DWU > SS: + 4.2%	0.4	< 0.05
							20-m sprint time	DWU < SS: − 1.4%	0.34	< 0.05

Table 2 continued

References	*n*	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	*P* value
Torres et al. [114]	11	Sternocleidomastoid, pectoralis major and minor, trapezius, latissimus dorsi, deltoids, rhomboids, teres major and minor, subscapularis, biceps brachii, brachialis, brachioradialis, triceps, serratus, obliques, intercostals, quadratus lumborum, erector spinae	DS	NR	30-reps × 7 stretches	NR	30% 1RM bench throw power	DS (+ 0.12) = NS	0.008	> 0.05
							30% 1RM bench throw force	DS (− 3.6) = NS	0.3	> 0.05
							30% 1RM bench throw velocity	DS (+ 0.55) = NS	0.09	> 0.05
							30% 1RM bench throw displacement	DS (+ 2.2) = NS	0.17	> 0.05
Turki et al. [57]	16	Quadriceps, hamstrings, gluteals, adductors, gastrocnemius	DE	ROM	DE1: 14 reps (20 m) × 5 exercises × 1	Actively, rapidly	10-m sprint time	DE1: No change: NR	NR	> 0.05
								DE2: No change: NR	NR	> 0.05
					DE2: 14 reps (20 m) × 5 exercises × 2			DE3: No change: NR	NR	> 0.05
							20-m sprint time	DE1: − 2.6%	1.17	0.001
					DE3: 14 reps (20 m) × 5 exercises × 3			DE2: − 2.6%	0.91	0.001
								DE3: + 2.6%	1.27	0.001
Unick et al. [92]	16	Quadriceps, hamstrings, calves	BS	NR	15-s × 3 sets × 4 stretches	1:1-s	CMJ height	No change: − 2.63%	0.18	> 0.05
							DJ height	No change: − 1.39%	0.1	> 0.05
Van Gelder and Bartz [69]	60	Erector spinae,romboids, pelvic, quadriceps, hamstrings, iliopsoas, gluteals, hip flexors, hip adductors, hip abductors, gastrocnemius, soleus	DE	ROM	4–20 reps × 1 set × 14 exercises	Controlled movement	Agility run time	DE < NS: − 4.31%	0.83	0.026
Vetter [123]	26	Quadriceps, hamstrings, gluteus, calves	DS	NR	8 reps × 4 stretches	Slowly	30-m sprint time	DS = NS: + 0.41%	0.03	> 0.05
							CMJ height	DS = NS: − 0.47%	0.06	> 0.05
Wallmann et al. [29]	25	Ilio-psoas	DS	NR	15-s × 2 sets	NR	40-yard sprint time	No change: + 0.86%	0.1	0.022
			BS		15-s × 2 sets			No change: − 0.34%	0.04	0.217
Werstein and Lund [71]	15	Quadriceps, hamstrings, gluteus maximus, gastrocnemeus	DS	NR	10 reps × 3 sets × 4 stretches	NR	Contact time	DS = NS: NR	NR	> 0.0167
							Flight time	DS > NS: NR	NR	< 0.0167
							Reactive strength index	DS > NS: NR	NR	< 0.0167

Table 2 continued

References	*n*	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	*P* value
Wiemann and Hahn [4]	69	Hamstrings	BS	NR	15-s × 3 sets × 3 stretches	Rhythmically	ROM	+ 7.46%	0.69	< 0.01
							End ROM torque	+ 13.6	0.54	< 0.05
							Passive muscle stretching tension	No change: − 0.43%	0.01	> 0.05
Yamaguchi an Ishii [56]	11	Quadriceps, hamstrings, hip extensors, hip flexors, plantar flexors	DS	NR	15-reps × 5 stretches	1:1-s 5 × Slowly and 10 × as quickly as possible	Leg extension power	+ 9.13%	1.47	< 0.01
Yamaguchi et al. [129]	7	Hip extensors, hip flexors, leg extensors, leg flexors, plantar flexors	DS	NR	10 reps × 1 set × 5 stretches (6-min 37 ± 12-s)	30 beats/min As quick as possible	Time to exhaustion	DS > NS: +15.43%	1.56	< 0.01
							Total distance	DS > NS: +15.84%	1.55	< 0.01
Zourdos et al. [50]	14	Quadriceps, hamstrings, hip extensors, hip flexors, calves	DE	NR	4 reps × 2 sets × 10 exercises (15-min)	NR	Hamstring flexibility	+ 14.09%	0.63	< 0.05
							Resting VO_2	+ 26.19	1.15	< 0.05
							Caloric expenditure	DE > NS: + 4.17%	0.4	< 0.05
							Distance run	DE < NS: − 3.17%	0.2	> 0.05

The outcomes and percentage changes were expressed relative to the control condition (/NS: % changes) or to the pre-stretching values (% changes). Comparisons with static stretching were not considered, except when control condition or pre-stretching values were lacking. DE was used when dynamic stretching was performed while walking. DWU was used when dynamic stretching was accompanied by other warm-up activities

NR not reported, *NS* no stretching, *BS* ballistic stretching, *DS* dynamic stretching, *DE* dynamic exercise, *DWU* dynamic warm-up, *FDE* fast dynamic exercise, *SDE* slow dynamic exercise, *SS* static stretching, *ROM* range of motion, *ISOK* isokinetic dynamometer, *CMJ* countermovement jump, *DJ* drop jump, *PT* peak torque, *RM* repetition maximum, *RSA* repeated sprint ability has also been shown to be more efficient than no-stretch [45, 56, 60, 63–72] and than static stretching [45, 51, 56, 63, 66–88]. While dynamic stretching predominantly leads to performance improvements, many studies showed no effects [4, 29, 38, 44, 46, 49, 61, 72, 73, 79, 80, 84, 88, 90, 92, 95, 99, 109, 113–124] or even an impaired performance [41, 42, 47, 57, 86, 88–90]. Table 2 illustrates studies outlining dynamic stretch-induced effects on force, power, jump height, sprint or agility and others such as balance, VO_2, etc.

Most studies have demonstrated significant enhancements of force and power [41, 51, 52, 56, 58, 61, 62, 66, 71, 125] or no adverse effects [4, 38, 61, 84, 89, 95, 101, 102, 109, 114, 119, 120, 124] with dynamic stretching. To our knowledge, four studies have reported significant decrements in force and power [41, 47, 86, 89, 90]. In the first study [47], force decreases could be explained by the fact that subjects performed unassisted and assisted stretches. In the second study [41], strength was measured after dynamic stretches in isometric conditions while enhancements were generally obtained during dynamic tasks. Then, Costa et al. [89] performed controlled repetitions of dynamic stretching whereas Sekir et al. [58] and Yamaguchi et al. [56] stretched 'as quickly and powerfully as possible'. Finally, Samuel et al. [90] and Sá et al. [86] used ballistic stretching, which may be less recommended than dynamic stretching. Although there is strong evidence regarding the positive or neutral effects of dynamic stretching on force and power, most of studies presented small or moderate effect sizes [41, 51, 61, 62, 66, 89, 95, 101, 102, 114, 119].

Regarding jump height, similar conclusions were reported. Studies generally registered increases [39, 45, 53, 54, 66, 70, 81, 82] or no effects [46, 54, 72, 79, 80, 90, 92, 95, 99, 102, 113, 115, 118, 121, 123] while only one study reported impairment of jump height after dynamic stretching [42]. Nevertheless, these changes were not different from the control condition without stretching. Again, many of these studies presented small effect sizes [45, 46, 54, 66, 70, 72, 82, 92, 99, 102, 118, 123].

During sprint running, velocity or agility, most studies reported performance enhancements [39, 44, 55, 57, 59, 64–66, 69, 70, 72, 81–83] or no adverse effects [29, 116, 122, 123]. Nevertheless, some have reported an impairment of the 20-m sprint velocity [42, 57, 88]. This could be partly due to the use of ballistic stretching [88] and the fatigue induced by the longer duration of dynamic stretching [57]. Nowadays and in accordance with the literature, dynamic stretching appears to be more appropriate than static stretching for subsequent performance. However, most of these studies have reported small effect sizes, which raises the need for further studies with larger sample sizes or more homogeneous groups of participants. Moreover, some mitigating factors such as stretching duration, amplitude or velocity may influence the stretch-induced effects. In Sect. 4, we consider these aspects to bring out the stretch effects on subsequent performance and the underlying physiological mechanisms.

4 Dynamic Stretching Variables

4.1 Effect of Stretching Duration

The magnitude of the stretch-induced effects can be attributed to several factors such as specific characteristics of stretching interventions [12]. For example, it is well established that static stretching-induced force decreases are dependent on stretch durations; the longer the stretch duration, the greater the force reductions [12, 15]. Concerning dynamic stretching, findings seem to be similar. Behm and Chaouachi [12] demonstrated greater percent enhancement in force and isokinetic power with dynamic stretching lasting longer than 90 s (7.3 ± 5.3%) as compared with shorter stretch durations (0.5 ± 2.3%) [38, 58, 64, 90, 92, 95, 113–115, 124, 126]. Nonetheless, studies with short dynamic stretch durations demonstrated positive effects on performance [54, 56, 100]. For instance, Yamaguchi et al. [56] used one set of 30-s dynamic stretching per muscle group and found a ~ 10% increased leg extension power (ES = 1.47, large effect). On the other hand, with longer stretch duration, Ryan et al. [39] suggested that two dynamic stretching routines lasting approximately 6 and 12 min resulted in similar improvements in vertical jump height (ES = 0.41, moderate effect and 0.37, small effect, respectively) and velocity (ES = 0.58 and 0.45, moderate effects, respectively). Similarly, Mizuno et al. [52] reported no change in end ROM passive torque after one, four and seven sets of dynamic stretching. Also, Turki et al. [57] reported a similar 20-m sprint time decrease (enhanced sprint performance) after one and two sets of 14 repetitions of dynamic stretching per muscular group (ES = 1.17 and 0.91, large effects, respectively). These studies suggest that the stretch duration effect is not so obvious. Nevertheless, while one and two sets of dynamic stretching have shown similar significant enhancements in 20-m sprint velocity, three sets have induced a significant reduction (ES = 1.27, large effect) [57]. Similarly, Sekir et al. [58] reported increases in concentric (ES = 1.11, large effect) and eccentric (ES = 1.7, large effect) hamstring peak torque after 6 ± 1 min of dynamic stretching while Costa et al. [89] found decreases with a much greater duration of 16.1 ± 2.6 min (ES = 0.44 and 0.69, moderate effects, for concentric and eccentric, respectively). This might be due to progressive fatigue, which could temporally overcome positive stretch-induced effects [57]. Accordingly, dynamic stretch duration does not seem to influence the subsequent muscular performance, for as long as fatigue stays insignificant. Future studies are needed to determine the optimal stretch duration producing positive effects on subsequent muscular performance without any fatigue production.

Methodologically, the units used to quantify stretch volume have varied greatly, e.g. duration in seconds [38, 79, 92], repetition number [58, 109, 114] or distance in meters [45, 64, 66]. Jaggers et al. [95] even compared two sets of 30-s ballistic stretching and two sets of 15-repetition dynamic stretching. Such non-homogeneous descriptions do not allow a clear understanding of the dose–response effects. The total duration of the stretching protocol, including multiple muscular groups, has also been reported [39, 45, 46, 66]. This hampers any comparison with studies expressing stretch duration per muscular group [41–43]. To facilitate inter-study comparisons, authors should report findings in terms of frequency (number of movements per second) and stretch duration per muscle group expressed in seconds, a unit commonly used in static and proprioceptive neuromuscular facilitation (PNF) stretching procedures.

4.2 Effect of Stretching Amplitude

The amplitude of stretching, which may be related to ROM, has also been shown to influence the magnitude of static stretch-induced effects [12, 28]. No study examined the effects of dynamic stretching amplitude on subsequent muscular performance. Although some studies do not specify this variable [4, 29, 38, 42, 43, 45, 50, 53, 54, 56, 58–60, 62, 64–68, 71, 74, 81, 84, 86, 89, 92, 101, 109, 114, 115, 118, 120–122, 128, 129], most studies performed stretching through the full active ROM. Among them, a distinction could be made between dynamic and ballistic stretch modalities. As a result of the inherent uncontrolled movement, one can argue that ballistic stretching allows moving the joint through a larger ROM than dynamic stretching. Indeed, it creates forces within muscles that can exceed the muscle extensibility and induce a greater tension in the muscle [93–96]. Moreover, the muscle, which is not held at the higher tension, does not have enough time to reduce tension or increase length [130, 131]. Given that, it has been suggested that ballistic stretching may be more harmful than other stretching techniques and has a greater likelihood of causing strain injuries [96, 111, 130, 131]. This distinction between these two types of stretching may help in understanding some apparent conflicting results. Indeed, studies using ballistic stretching mostly reported neutral [4, 29, 38, 90, 92, 95, 101, 113] or negative effects [47, 86, 88, 90, 101] on subsequent muscular performance while dynamic stretching mostly produced positive effects. To avoid any misinterpretations, studies need to clearly describe their stretching protocols and more particularly stretch amplitude.

4.3 Effect of Stretching Velocity

The effects of stretching velocity on subsequent performance have not been fully examined. Indeed, to our knowledge, only one study compared two different dynamic stretch velocities [54]. Authors have shown that the faster velocity of stretching (100 beats·min^{-1}) resulted in higher vertical jump height than the slower velocity (50 beats·min^{-1}). The literature seems to be consistent with these observations. Fast stretching velocities (stretched muscles ‘quickly’ or ‘as quickly as possible’) mainly demonstrated an enhancement of muscular performance [53, 54, 56, 58, 64, 74]. In contrast, studies that used slow and moderate speed or did not set the velocity more likely showed neutral or negative effects [38, 41–43, 46, 47, 54, 55, 61, 79, 86, 92, 109, 113, 123, 124]. For instance, Hough et al. [53] reported an increase in countermovement jump (CMJ) height after dynamic stretching performed slowly and then as quickly as possible, contrary to Morrin et al. [80] who did not find any positive effect of dynamic stretching carried out at a moderate intensity pace (ES $=$ 0.81, large effect). Moreover, a recent review [97] suggested that the rate of change in explosive performance is significantly greater with faster dynamic stretching. It has been hypothesized that a fast stretching velocity would induce increased heart rate and core temperature [56]. However, in a recent study [54], core temperature was not significantly altered with the different velocities. The significant increase in jump performance with the faster stretching velocity was probably linked to a greater increase in EMG magnitude. The authors supposed that the faster stretch condition, which involves a faster stretch-shortening cycle, evoked segmental reflexes potentiating the subsequent muscle activation and by consequence the subsequent power production [54].

In addition, methodologically, many studies attempted to define the velocity using approximate terms such as ‘rhythmically’, ‘at a slow to moderate cadence’, ‘slowly and quickly’ or ‘as quick as possible’ [4, 39, 41, 64, 66, 74]. However, these terms do not provide enough description to understand how stretch is performed. A stretching description should also include the modality used, i.e., whether it is performed in uncontrolled versus controlled conditions (ballistic or not, respectively). Indeed, uncontrolled movements imply stretching as fast as possible. Although difficult, we suggest that the stretching description must take into account the type (dynamic or ballistic, controlled or uncontrolled movement, with bouncing or without bouncing), the velocity (slow, moderate, quick speed or as fast as possible) and the frequency (number of movements per second) of stretch.

4.4 Standing Versus Walking Stretching

Dynamic stretching may be performed standing upright, or during dynamic tasks (e.g. walking, high knees, backward reach run, straight leg skipping, running cycles, bilateral hops, etc.). Indeed, some authors defined dynamic exercises (DE) as activities that consist of performing the same movement as the dynamic stretching but walking [85]. Additionally, dynamic warm-up (DWU) includes single joint dynamic stretching (like flexion and extension of the hip), often paired with multiple joint dynamic stretches (like squat or lunge), running drills [66], agility and plyometric activities, and specific motor pattern movements [102]. Standing upright stretching has shown neutral [29, 55, 61, 79, 80, 84, 89, 92, 99, 114, 116, 119, 121, 123, 124] or positive [52, 53, 56, 61, 62, 67, 70, 71, 74] effects on subsequent performance. While walking, dynamic stretching has mainly demonstrated positive effects [39, 45, 50, 55, 57, 59, 60, 63, 64, 68, 69, 72, 87, 100]. For instance, Paradisis et al. [42] have shown an increase in 20-m sprint time after 40 s of dynamic stretching per muscular group with a frequency of 1 Hz (ES = 0.1, small effect). In contrast, Little and William [63] reported an increase in 20-m sprint velocity after a similar stretch duration and frequency (i.e. 30 s per muscular group with a frequency of 1 Hz) but while walking. Additionally, Fletcher et al. [55] compared standing versus walking stretching [55]. They reported that dynamic stretching while walking positively affected sprint performance compared to standing stretch. This may be linked to the rehearsal of movement in a more specific pattern (see below) [55]. Indeed, proprioception and pre-activation, which are required in sprinting to help the rapid transition from eccentric to concentric contraction, may be invoked during walking [76]. Performing dynamic stretching while walking could help rehearsal of specific movement patterns allowing muscles to be excited earlier and faster, therefore producing more power and decreasing sprint time [55]. Another possibility is that during plyometric exercises like walking or during dynamic stretching, a rapid stretch would stimulate the muscle spindles causing an increase in the muscle's reflex activity and thus a potentiated activity of the agonist muscle [95]. Finally, it could be attributed to temperature- and/or nervous-related mechanisms. In fact, physiological mechanisms by which dynamic stretching enhance muscular performance may be exacerbated when stretches are performed during dynamic tasks.

4.5 Effect of the Studied Population

The magnitude of the stretch-induced effects may be attributed to stretch characteristics but also to the studied population. Indeed, different factors (such as sex, age, physical training level, flexibility level, muscle group or training modality) may affect musculotendinous stiffness or viscoelastic properties [12]. For instance, some studies have reported differences in the viscoelastic properties of muscle and tendon structures between men and women [132, 133] and with age [134]. For instance, authors reported no change in jump performance and an enhancement in balance after 90 s of static stretching in middle-aged active adults, while decrements are usually observed in younger populations [135]. In addition, it has been suggested that trained athletes are less susceptible to stretching-induced changes than untrained athletes [92, 136, 137]. Moreover, it has been shown that the acute effects of stretching on torque production were dependent on the individual's flexibility [138]. Indeed, the authors reported lower torque decreases in more flexible individuals. Quite similarly, some studies have suggested that stretching effects are dependent on the intrinsic stiffness of the MTU, which is muscle-specific [139, 140]. Indeed, stretching effects would mainly occur in stiff tissues. In the same way, Lima et al. [141] suggested that ballistic stretching may have a positive warm-up effect on muscular endurance in flexible populations, as they found a decrease in muscular fatigue in ballet dancers but not in resistance-trained women. With the exception of this last-cited study, the influence of these different factors on the stretch-induced effect has mostly been investigated with static stretching. Although we expected similar behaviours with dynamic stretching, further studies should focus on this point.

5 Physiological Mechanisms

Unlike static stretching, dynamic stretching is nowadays recommended as a pre-performance routine. However, there is little knowledge regarding the underlying mechanisms of stretch-induced performance enhancement. Mechanisms have been hypothesised to be neural and peripheral in nature.

5.1 Heart Rate, Muscle and Core Temperature

Muscular performance improvements after a single bout of dynamic stretching are likely attributed to the associated voluntary contractions. Because muscles are contracting actively and rhythmically to stretch, dynamic stretching may help in the warm-up process, increasing heart rate and also core and muscle temperature [54, 56, 72, 108, 109]. Studies have shown significant increases in heart rate after dynamic stretching compared to static or no-stretch conditions [54, 72, 108]. For instance, Fletcher and Monte-Colombo [108] reported that heart rate after dynamic stretching (158 ± 15 beats·min^{-1}) was significantly higher ($P < 0.001$) than after no stretching (130 ± 12 beats·min^{-1}) and static stretching (92 ± 14 beats·min^{-1}). They also measured core temperature, and reported that dynamic stretching induced the greatest temperature rise (+ 0.18 and + 0.19 °C) compared to no-stretch and static stretching, respectively. Nevertheless, core temperature was recorded at the tympanum. Therefore measurements were lower than could be expected and accuracy can be questioned as compared with rectal, oesophagus or muscular measurements [1, 142]. Thus, to strengthen the clinical significance of such findings, further experiments should determine the effects of dynamic stretching on muscular temperature. Moreover, it would be interesting to examine the specific effects of dynamic stretching parameters (i.e. type, duration and velocity) on these temperature-related mechanisms.

5.2 Muscle–Tendon Unit (MTU) Stiffness

One other possible effect of the increased muscular temperature is a decrease in the viscosity [1, 143], lowering resistance to stretch and increasing joint ROM [107]. Thus, we could expect a decrease in MTU stiffness. The literature has focused on dynamic stretching effects resulting from temperature-related mechanisms, but the effects on mechanical properties and more particularly on MTU stiffness need to be investigated further. Unlike static stretching, and due to few studies, the effects of dynamic stretching on MTU stiffness remain unclear. Some authors [54, 108] have used an estimation of stiffness from total knee movement during vertical jumps (as suggested by Knudson et al. [127]). Indeed, if stretching decreases stiffness of the effector muscles, lower knee flexion angles could be expected, i.e. a larger ROM. Fletcher et al. [54, 108] reported that knee ROM was significantly greater in countermovement jump and drop jump for the dynamic stretching as compared with no-stretch.

Furthermore, passive MTU stiffness has been widely determined from the relationship between joint angle and passive torque [134, 144–146]. Herda et al. [41] quantified passive muscle stiffness using a fourth-order polynomial regression model that was fitted to the passive torque–angle curves for each participant. Results reported that passive resistive torque and passive stiffness decreased following 2 min of dynamic stretching. These changes indicated modifications in the viscoelastic properties of the MTU and the authors suggested that viscosity could be specifically affected. Similarly, Nordez et al. [147] have reported that viscosity plays a major role in passive stiffness changes during cyclic stretching protocols and proposed it may be likely due to the rearrangement/slipping of collagen fibres. Imaging techniques such as ultrasonography provide information on changes in muscle fascicle length and tendinous tissue behaviour [34, 35, 49, 139, 148, 149] that can be used to directly measure changes in MTU, muscle or tendon stiffness. Recently, some authors used this technique to assess stiffness changes after dynamic [52, 128] and ballistic [49] stretching. The first two studies did not reveal any change in the passive mechanical properties of the MTU: MTU stiffness, passive resistive torque and displacement of the muscle–tendon junction were unaffected by four sets [52] and seven sets [128] of 30-s dynamic stretching. Inversely, 4×30-s of ballistic stretching was sufficient to decrease MTU stiffness, muscle stiffness and passive resistive torque [49]. Dynamic and ballistic stretching seem to differently affect the passive mechanical properties of the MTU as a result of the different ROM achieved during stretching. Indeed, the larger ROM achieved during ballistic stretching likely induces greater decreases in MTU stiffness. Moreover, the decrease in stiffness may be linked to the higher intensity movement in the ballistic stretch, potentially causing a greater increase in muscle temperature. It has been proposed that an increase in temperature may decrease the viscous resistance of muscles [110] and by consequence reduce passive resistive torque and MTU stiffness. Nevertheless, additional studies are clearly needed to discriminate the effects of dynamic and ballistic stretching on MTU stiffness, and specifically on contractile and non-contractile elements.

5.3 Post-activation Potentiation

As hypothesised by previous authors, dynamic stretching might also produce post-activation potentiation (PAP) [53, 78, 81, 114, 150]—a transient improvement of muscular contractility following a conditioning voluntary contraction [151]. While it has been hypothesised that dynamic stretching could induce PAP, it is more likely associated with high force activities [152]. Also, it would be linked to the degree of muscular recruitment of the conditioning contraction [152]. According to Henneman's size principle [153], it has been suggested that heavier loadings, resulting in superior activation of type II muscle fibre motor units, induce more favourable PAP adaptations than lighter loadings [152]. However, some studies suggested that ballistic contractions may provide an effective stimulus for PAP [152, 154]. Indeed, Baudry and Duchateau [154] reported a ballistic contraction-induced twitch potentiation related to a greater number of motor unit involvement compared with sustained submaximal contraction performed at similar intensity. If PAP is dependent on the degree of muscular recruitment, this would partly explain why faster dynamic stretching could induce increases in jump performance as compared to slow dynamic stretching [54]. The principal mechanism of PAP is a higher rate of cross-bidge formation [154, 155], which relies on the phosphorylation of myosin regulatory light chains that render actin-myosin interaction more sensitive to Ca^{2+} release from the sarcoplasmic reticulum [151, 156, 157]. It would shorten the time to peak torque and increase the rate of torque development, increasing muscular force, power and speed in subsequent performance [150, 151]. For instance, Yamaguchi et al. [158] reported a decrease in time to peak torque and an increase in the rate of torque development subsequent to dynamic stretching. They concluded from their results that PAP might occur. According to the literature, voluntary contractions associated with dynamic stretching would induce such potentiation; this is currently considered as one of the most relevant explanations of stretch-induced alterations. Some authors suggested that PAP after dynamic stretching could also originate from an enhanced excitation of the neuromuscular system [54]. Indeed, an increase in EMG has previously been registered after dynamic stretching [54]. Such a hypothesis was developed in a recent review [152]. Nevertheless, to our knowledge, no study has specifically measured the PAP phenomenon after a single bout of dynamic stretching. Further investigations are needed to assess the real impact of dynamic stretching on potentiation-related mechanisms.

5.4 Rehearsal of Movement

The other possibility for the positive changes in performance observed after a bout of dynamic stretches may be the rehearsal of movement in a specific pattern [55, 63, 76]. Fletcher and Jones' study [55] among rugby union players speculated that improvements in explosive activities (20-m sprints) were related to increased muscular coordination following a dynamic stretching routine. Indeed, they suggested that the rehearsal of specific movement patterns through dynamic active stretching may increase coordination, which allows the muscle to transition more quickly from the eccentric to the concentric phase of contraction, required to generate running speed. Moreover, performing dynamic stretching while walking could help rehearsal of specific movement patterns allowing proprioception and preactivation, which are required in sprinting or jumping [55, 76]. Another possibility is that dynamic stretching stimulates the muscle spindles similar to plyometric training, causing an increase in muscle reflex activity and thus potentiated activity of the stretched muscle [95]. This increase in potentiation should result in increased force and vertical jump height, partly explaining the dynamic stretch-induced effects. However, this mechanism has not been fully explored and needs to be investigated further.

5.5 Neural Adaptations

Stretch-induced effects may also be attributed to neural factors such as motor unit activation or reflex sensitivity [53, 54, 56, 78]. In the literature, the increase in electromyography after dynamic stretching suggests that neuromuscular mechanisms were also responsible for the subsequent enhanced muscular performance [53, 54, 58, 109], especially following fast dynamic stretches [54]. Indeed, Fletcher [54] has demonstrated an increase in EMG in a fast dynamic stretching intervention (100 beats·min^{-1}), and no changes in slow dynamic stretching intervention (50 beats·min^{-1}). Such EMG augmentation may represent greater motor-unit activation [53, 54, 109] through neuromuscular propagation [53] and/or increased motor-unit recruitment and synchronization [159]. Authors have suggested that this likely enhancement of neuromuscular function would result from higher core and muscular temperature [58, 78, 108, 150]. Indeed, elevated core and muscle temperature, induced by the contractions of dynamic stretching, may increase nerve conduction velocity and the sensitivity of nerve receptors.

Improvement in neuromuscular performance after dynamic stretching has also been associated with changes in reflex sensitivity [54, 95, 109]. Contrary to static stretching, fast lengthening would not decrease reflex activity of stretched muscles, but instead would increase spinal reflex activity [112]. H-reflex is widely used to study changes in the reflex excitability of groups of muscle fibres and could reflect spinal and alpha-motoneuron excitability [160]. Vujnovich and Dawson [161] compared the effects of static stretching and static stretching immediately followed by ballistic stretching on changes in the H-reflex. These authors reported that static followed by ballistic stretching demonstrated greater decline in H-reflex amplitude than static stretching only. This decline reflected an inhibition of the alpha-motoneuron pool during ballistic muscle stretching. They suggested it might implicate a significant inhibitory contribution from Golgi tendon organs. These receptors are relatively insensitive to passive, slow velocity length changes of muscle [162], but respond mainly to rapid and large-amplitude stretch and to the end-range forces applied, by decreasing the motoneuron excitability [163, 164]. Presynaptic inhibition mediated by muscle spindle type Ia afferents discharging during ballistic stretch [164] is also a candidate for inhibition of the alpha-motoneuron. Conversely, Clark et al. [121] reported a significant decrease in presynaptic inhibition after dynamic stretching and no change after static stretching. They hypothesised that the rapid elongation and contraction of the muscle fibres, which are not present in static stretching, may explain this decrease. Nevertheless, in view of the lack of studies on this topic, further investigations are needed to explore the changes in spinal excitability after dynamic and ballistic stretching. An alternative hypothesis is that the changes in EMG activity would originate from changes in supraspinal drive. Several authors have suggested that input from stretch sensitive afferents might modulate corticospinal excitability [165]. Indeed, muscle lengthening has been shown to reduce corticospinal excitability [164, 165], in contrast to muscle shortening that would potentiate motor-evoked potential amplitudes [165]. However, the effects of dynamic stretching (repetitive and rapid lengthening) on cortical excitability have never been studied.

6 Limitations

When assessing the literature, it is sometimes difficult to make pertinent comparisons between studies. Indeed, lack of sufficient information concerning certain factors such as sex, muscle group, control during stretching (frequency or ROM achieved during stretching), or stretching and warm-up procedures, together with an inconsistent nomenclature describing the type of stretch used, hampers interpretation of data in the literature. The difference between dynamic stretching and ballistic stretching is not always taken into account, and dynamic stretching versus dynamic activities is not well defined in many studies. Some studies are not clear in the description of their experimental protocols, and do not control with accuracy stretch interventions. Moreover, methodological problems remain a deterrent to determining underlying mechanisms. Indeed, dynamic stretching is necessarily a high velocity activity incompatible with assessment techniques such as ultrasonography or nerve stimulation.

7 Conclusion and Recommendations

There is a strong body of evidence supporting the positive or neutral effects of dynamic stretching on subsequent muscular performance. The few studies reporting impaired performance highlighted possible mitigating factors. Ballistic stretching would be less beneficial than dynamic stretching, because of the larger end ROM and rebound. High velocity stretching seems to positively affect subsequent muscular performance. Moreover, effects on performance may be amplified when stretches are performed while walking. Unlike what might have been expected, stretching duration does not seem to affect subsequent muscular performance, at least until fatigue becomes too important. Taking these mitigating factors into account, dynamic stretching represents a more efficient modality than static stretching to be employed prior to subsequent muscular performance, and especially prior to explosive or high-speed activities. Mechanisms by which it may improve muscular performance are still unclear. However, it has been hypothesised that it could be mainly attributed to associated voluntary contractions and thus to temperature and potentiation-related mechanisms. MTU stiffness might be impaired, explaining in part the potentially improved ROM after dynamic stretching, but seems not to be primarily responsible for stretch-induced performance enhancement. Nevertheless, only a limited number of studies have explored physiological mechanisms and further studies are needed. Finally, to achieve a clear consensus on the dynamic stretch-induced effects, studies should use common terminology and methodological rules. We recommend distinguishing dynamic stretching, which involves controlled movements without bouncing, from ballistic stretching, which is characterised by uncontrolled and bouncing movements. In addition, we propose that dynamic stretching performed while moving (i.e. walking) be termed dynamic exercise, and that dynamic stretching paired with other activities or multiple joint dynamic stretches be defined as dynamic warm-up. In addition to the type of stretching, the description should include stretch duration per muscular group (in seconds), stretch frequency (number of movements per second), stretch velocity (slow, moderate, quick speed or as fast as possible) and stretch amplitude (in full or in percentage of the active range of motion).

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Compliance with Ethical Standards

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