

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

Jules Opplert^{1,2} · Nicolas Babault^{1,2}

Published online: 23 October 2017
© Springer International Publishing AG 2017

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

✉ Jules Opplert
opplert.jules@gmail.com

¹ INSERM CAPS, UMR 1093, Faculté des Sciences du Sport, Université de Bourgogne-Franche-Comté, BP 27877, 21078 Dijon Cedex, France

² Centre d'Expertise de la Performance, Faculté des Sciences du Sport, Université de Bourgogne-Franche-Comté, BP 27877, 21078 Dijon Cedex, France

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

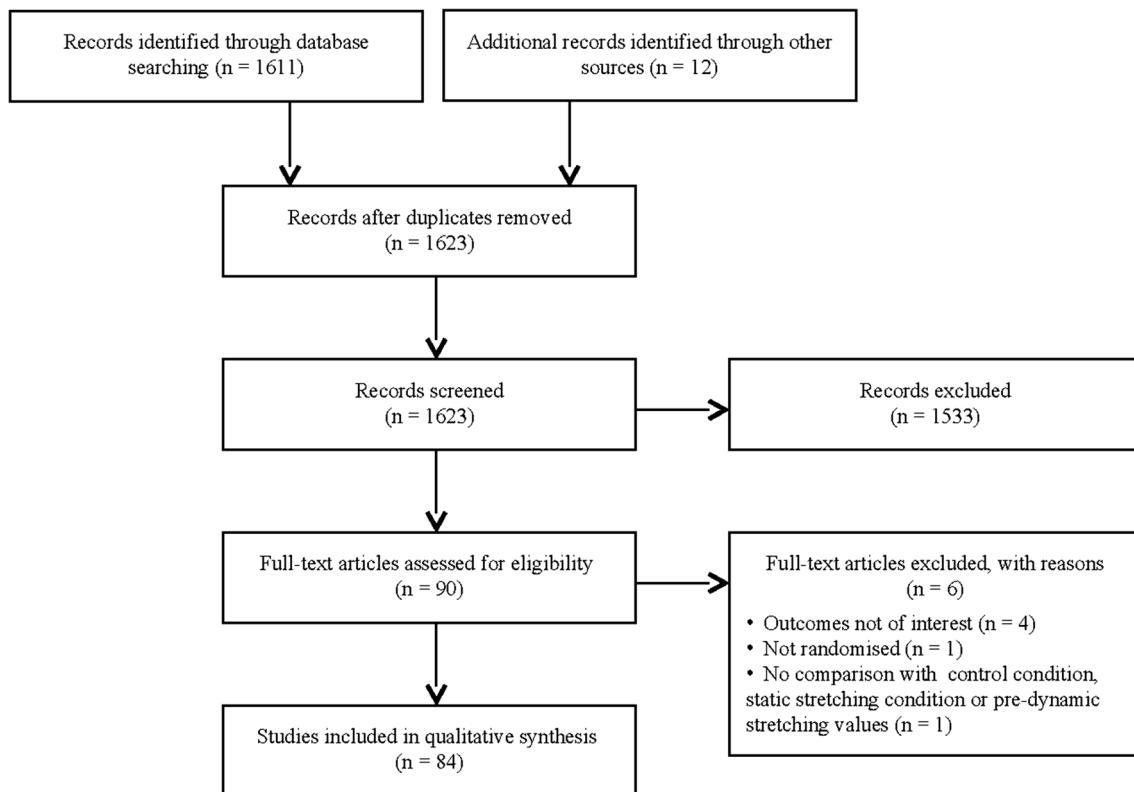


Fig. 1 Flowchart illustrating the search strategy

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

Table 2 continued

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

Table 2 continued

References	<i>n</i>	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	<i>P</i> 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 SJ height	DS = NS: NR DS = NS: NR	NR NR	> 0.05 > 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) Agility time Movement time	DE > NS: + 12.3% DE > NS: + 3.54% DE > NS: + 5.97%	0.4 0.54 0.46	< 0.05 < 0.05 < 0.05
Chatzopoulos et al. [122]	27	Deltoid, pectoral, triceps, quadriceps, hamstrings, adductors, gastrocnemius	DE	NR	18-m × 7 exercises (5-min)	NR	Reaction time Reaction time Movement time	DE (- 0.53%) = NS DE = NS: 0% DE = NS: - 2.73%	0.03 0.0 0.18	> 0.05 > 0.05 > 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 Concentric hamstrings PT	60°/s: No change: - 1.64% 180°/s: No change: - 0.54%	0.06 0.02	> 0.05 > 0.05
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	Eccentric hamstrings PT ROM quadriceps CMJ height Time to peak force	60°/s: - 10.0% 180°/s: - 10.6% 60°/s: - 16.04% 180°/s: - 13.7% + 6.03% No change: + 1.89% No change: 27.27%	0.69 0.67 0.46 0.13 0.59	< 0.05 < 0.05 < 0.05 < 0.05 < 0.05 > 0.05 > 0.05

Table 2 continued

References	<i>n</i>	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	<i>P</i> 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, gastrocnemius, 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	DE = NS: + 1.89% DE < NS: - 2.99%	0.19 0.69	> 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 Balsom agility (s)	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) Time to peak power (Wingate) Peak power (Wingate)	DS = NS: NR DS > NS: NR	NR NR	> 0.05 < 0.001
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 Slalom dribbling time Penalty kick speed	DE < NS: - 4.1% DE < NS: - 5.1% DE > NS: + 3.3%	0.95 1.20 1.25	< 0.03 < 0.01 < 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 10-m sprint time 20-m sprint time 30-m sprint time	DS > NS: + 1.6% DS < NS: - 2.1% DS < NS: - 1.0% DS < NS: - 1.1%	0.4 0.76 0.55 0.7	0.000 0.000 0.000 0.000
Hayes and Walker [103]	7	Quadriceps, hamstrings, gluteals, hip flexors, calves	DS	ROM	30-s × 5 stretches	Controlled velocity	RSA (s) Hamstring flexibility Running economy	DS (-0.22%) = NS +: NR DS = NS: NR	0.11 NR NR	> 0.05 < 0.05 > 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°) PT (80°) Passive ROM CMJ height	- 9.67% + 13.34% +: NR + 4.9%	0.32 0.47 NR NR	0.007 0.003 0.003 < 0.05
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				

Table 2 continued

References	<i>n</i>	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	<i>P</i> value
Jagers et al. [95]	10	Quadriceps, hamstrings, spinal erectors, sartorius, hip flexors, hip extensors, hip adductors, gastrocnemius	BS DE	ROM	15 reps × 2 sets × 5 stretches 30-s × 2 sets × 5 exercises	126 beats/min 5 × slowly and 10 × as quickly as possible	CMJ height Maximal power Maximal force	BS (+ 3.04%) = NS DE (+ 7.03%) = NS BS (+ 3.33%) = NS DE (+ 4.04%) = NS BS (+ 2.25%) = NS DE (+ 9.38%) = NS DE = NS; + 6.45%	0.16 0.36 0.15 0.18 0.07 0.37	0.37 0.13 0.56 0.07 0.77 0.52 NR
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 Mean anaerobic power	DE = NS; + 6.45%	NR	NR
Konrad et al. [49]	24	Plantar flexors	BS (ISOK)	ROM	30-s × 4 sets	1:1-s	Power drop Fatigue index ROM Passive resistive torque	DE = NS; NR DE = NS; NR DE = NS; NR + 4.36% - 11.56	NR NR NR 0.25 0.37	0.07 0.53 0.04 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 Bench press time to maximal isometric force Bench press rate of force production	+ 3.6% No change; + 4.69% No change; + 6.86%	0.19 0.14 0.2	< 0.05 > 0.05 > 0.05

Table 2 continued

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

Table 2 continued

References	<i>n</i>	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	<i>P</i> 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 × as quickly as possible	Vertical jump height ROM hip ROM knee Hamstrings flexibility	No change: + 1.96% No change: + 5.67% No change: + 0.19% + 7.72%	0.14 0.42 0.04 0.18	> 0.017 > 0.017 > 0.017 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 10-m sprint time 20-m sprint time	DE > SS: + 4.44% DE < SS: - 2.2% DE < SS: - 1.0%	NR NR NR	< 0.05 < 0.05 < 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 Knee-flexion IRM Knee-extension IRM	+ 8.3% BS < NS: - 7.23% BS < NS: - 5.23%	3.17 1.13 0.81	< 0.05 < 0.05 < 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 Flight time Step length Contact time 20-m sprint time	+ 1.7% + 5.8% + 2.2% No change: + 0.33% + 0.8%	0.14 0.3 0.33 0.0 0.1	< 0.05 < 0.05 > 0.05 < 0.05
Paradis et al. [42]	48	Quadriceps, hamstrings, hip extensors, plantar flexors	DS	NR	40-s × 4 stretches	1:1-s	CMJ height Hamstrings flexibility	- 2.2% + 6.5%	0.1 0.14	< 0.05 < 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 Vertical jump peak power	No change: + 3% No change: + 0.7%	NR NR	0.25 0.32

Table 2 continued

References	<i>n</i>	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	<i>P</i> 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 Hamstrings flexibility Reaction time	DWU > NS: + 3.72% DWU > NS: + 9.64% DWU (- 0.98%) = NS	0.24 0.41 0.08	0.005 < 0.001 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 CMJ velocity Hamstring flexibility Muscular endurance	DE1: + 6.2% DE2: + 5.6% DE1: + 6.1% DE2: + 4.8% DE1: + 10.7% DE2: + 8.2% DE1 = NS: NR DE2 < NS: -15.6%	0.41 0.37 0.58 0.45 0.4 0.35 NR NR	< 0.001 < 0.001 < 0.001 < 0.001 < 0.001 < 0.001 > 0.05 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 Total number of reps leg curl Total number of reps in session	BS < NS: - 14.11% BS < NS: - 20.97 BS < NS: - 10.19	NR NR NR	0.014 0.002 0.002
Samuel et al. [90]	24	Quadriceps, hamstrings	BS	ROM	30-s × 3 sets × 2 stretches	60 batt/min	Vertical jump height Vertical jump power Quadriceps torque Hamstrings torque	BS = NS: NR BS < NS: - 2.4% BS = NS: NR BS = NS: NR	NR NR NR NR	> 0.05 < 0.05 > 0.05 > 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	<i>n</i>	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	<i>P</i> 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 Eccentric quadriceps PT	60°/s: + 8.41% 180°/s: + 11.81% 60°/s: + 14.5% 180°/s: + 15.04%	1.12 1.5 1.95 2.11	< 0.001 < 0.01 < 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 0–5-m speed vaulting 5–10-m speed vaulting 10–15-m speed vaulting	DS = NS: NR DS = NS: NR DS = NS: NR DS = NS: NR	NR NR NR NR	> 0.05 > 0.05 > 0.05 > 0.05
Su et al. [51]	30	Quadriceps, hamstrings	DE	ROM	15 reps (30-s) × 3 sets × 2 exercises	Controlled movement	Quadriceps flexibility Hamstring flexibility Knee extension peak torque	+ 2.22% + 5.91% + 4.51%	0.46 1.10 0.45	< 0.05 < 0.05 < 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	Knee flexion peak torque Vertical jump height 20-m sprint time	No change: + 1.37% DWU > SS: + 4.2% DWU < SS: – 1.4%	0.14 0.4 0.34	> 0.05 < 0.05 < 0.05

Table 2 continued

References	<i>n</i>	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	<i>P</i> 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% IRM bench throw power 30% IRM bench throw force 30% IRM bench throw velocity	DS (+ 0.12) = NS DS (- 3.6) = NS DS (+ 0.55) = NS	0.008 0.3 0.09	> 0.05 > 0.05 > 0.05
Turki et al. [57]	16	Quadriceps, hamstrings, gluteals, adductors, gastrocnemius	DE	ROM	DE1: 14 reps (20 m) × 5 exercises × 1 DE2: 14 reps (20 m) × 5 exercises × 2 DE3: 14 reps (20 m) × 5 exercises × 3	Actively, rapidly	10-m sprint time 20-m sprint time	DE1: No change: NR DE2: No change: NR DE3: No change: NR DE1: - 2.6% DE2: - 2.6% DE3: + 2.6%	NR NR NR 1.17 0.91 1.27	> 0.05 > 0.05 > 0.05 0.001 0.001 0.001
Unick et al. [92]	16	Quadriceps, hamstrings, calves	BS	NR	15-s × 3 sets × 4 stretches	1:1-s	CMJ height DJ height	No change: - 2.63% No change: - 1.39%	0.18 0.1	> 0.05 > 0.05
Van Gelder and Bartz [69]	60	Erector spinae, rhomboids, 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
Wallmann et al. [29]	25	Ilio-psoas	DS BS	NR	15-s × 2 sets 15-s × 2 sets	NR	CMJ height 40-yard sprint time	DS = NS: - 0.47% No change: + 0.86% No change: - 0.34%	0.06 0.1 0.04	> 0.05 0.022 0.217
Werstein and Lund [71]	15	Quadriceps, hamstrings, gluteus maximus, gastrocnemius	DS	NR	10 reps × 3 sets × 4 stretches	NR	Contact time Flight time Reactive strength index	DS = NS: NR DS > NS: NR DS > NS: NR	NR NR NR	> 0.0167 < 0.0167 < 0.0167

Table 2 continued

References	<i>n</i>	Muscles stretched	Stretch protocol	Amplitude	Volume	Velocity/frequency	Performance	Outcome and percentage change	Effect size	<i>P</i> value
Wiemann and Hahn [4]	69	Hamstrings	BS	NR	15-s × 3 sets × 3 stretches	Rhythmically	ROM End ROM torque	+ 7.46% + 13.6	0.69 0.54	< 0.01 < 0.05
Yamaguchi and 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 Total distance	DS > NS: +15.43% DS > NS: +15.84%	1.56 1.55	< 0.01 < 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 Resting VO ₂ Caloric expenditure Distance run	+ 14.09% + 26.19 DE > NS: + 4.17% DE < NS: - 3.17%	0.63 1.15 0.4 0.2	< 0.05 < 0.05 < 0.05 > 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 ($7.3 \pm 5.3\%$) as compared with shorter stretch durations ($0.5 \pm 2.3\%$) [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 $\sim 10\%$ 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]. Jagers 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 ($100 \text{ beats}\cdot\text{min}^{-1}$) resulted in higher vertical jump height than the slower velocity ($50 \text{ beats}\cdot\text{min}^{-1}$). 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, Paradisi 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-bridge 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 ($100 \text{ beats}\cdot\text{min}^{-1}$), and no changes in slow dynamic stretching intervention ($50 \text{ beats}\cdot\text{min}^{-1}$). 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).

Acknowledgements The authors gratefully acknowledge Dr. Gerald G. Pope for carefully reviewing the manuscript and for correcting the English.

Compliance with Ethical Standards

Funding No sources of funding were used to assist in the preparation of this review.

Conflict of interest Jules Opplert and Nicolas Babault have no conflicts of interest to declare.

References

1. Bishop D. Warm up I: potential mechanisms and the effects of passive warm up on exercise performance. *Sports Med.* 2003;33:439–54.
2. Young WB, Behm DG. Should static stretching be used during a warm-up for strength and power activities? *Strength Cond J.* 2002;24:33–7.
3. Bandy WD, Irion JM, Briggler M. The effect of time and frequency of static stretching on flexibility of the hamstring muscles. *Phys Ther.* 1997;77:1090–6.

4. Wiemann K, Hahn K. Influences of strength, stretching acid circulatory exercises on flexibility parameters of the human hamstrings. *Int J Sports Med.* 1997;18:340–6.
5. Power K, Behm D, Cahill F, Carroll M, Young W. An acute bout of static stretching: effects on force and jumping performance. *Med Sci Sport Exerc.* 2004;36:1389–96.
6. Wilson GJ, Wood GA, Elliott BC. The relationship between stiffness of the musculature and static flexibility: an alternative explanation for the occurrence of muscular injury. *Int J Sports Med.* 1991;12:403–7.
7. Wilson GJ, Elliott BC, Wood GA. Stretch shorten cycle performance enhancement through flexibility training. *Med Sci Sport Exerc.* 1992;24:116–23.
8. Opplert J, Genty J-B, Babault N. Do stretch durations affect muscle mechanical and neurophysiological properties? *Int J Sports Med.* 2016;37:673–9.
9. Magnusson SP, Simonsen EB, Aagaard P, Sørensen H, Kjaer M. A mechanism for altered flexibility in human skeletal muscle. *J Physiol.* 1996;497(Pt 1):291–8.
10. Avela J, Kyro H. Altered reflex sensitivity after repeated and prolonged passive muscle stretching. *J Appl Physiol.* 1999;86:1283–91.
11. Babault N, Kouassi BYL, Desbrosses K. Acute effects of 15 min static or contract-relax stretching modalities on plantar flexors neuromuscular properties. *J Sci Med Sport Sports Med Aust.* 2010;13:247–52.
12. Behm DG, Chaouachi A. A review of the acute effects of static and dynamic stretching on performance. *Eur J Appl Physiol.* 2011;111:2633–51.
13. Cramer JT, Beck TW, Housh TJ, Massey LL, Marek SM, Danglemeier S, et al. Acute effects of static stretching on characteristics of the isokinetic angle—torque relationship, surface electromyography, and mechanomyography. *J Sports Sci.* 2007;25:687–98.
14. Fowles JR, Sale DG, Mac Dougall JD. Reduced strength after passive stretch of the human plantarflexors. *J Appl Physiol.* 2000;89:1179–88.
15. Kay AD, Blazevich AJ. Effect of acute static stretch on maximal muscle performance: a systematic review. *Med Sci Sport Exerc.* 2012;44:154–64.
16. Kay AD, Blazevich AJ. Isometric contractions reduce plantar flexor moment, Achilles tendon stiffness, and neuromuscular activity but remove the subsequent effects of stretch. *J Appl Physiol.* 2009;107:1181–9.
17. Kay AD, Blazevich AJ. Moderate-duration static stretch reduces active and passive plantar flexor moment but not Achilles tendon stiffness or active muscle length. *J Appl Physiol.* 2009;106:1249–56.
18. Weir DE, Tingley J, Elder GCB. Acute passive stretching alters the mechanical properties of human plantar flexors and the optimal angle for maximal voluntary contraction. *Eur J Appl Physiol.* 2005;93:614–23.
19. Winchester JB, Nelson AG, Kokkonen J. A single 30-s stretch is sufficient to inhibit maximal voluntary strength. *Res Q Exerc Sport.* 2009;80:257–61.
20. Behm DG, Bambury A, Cahill F, Power K. Effect of acute static stretching on force, balance, reaction time, and movement time. *Med Sci Sport Exerc.* 2004;36:1397–402.
21. Cornwell A, Nelson AG, Sidaway B. Acute effects of stretching on the neuromechanical properties of the triceps surae muscle complex. *Eur J Appl Physiol.* 2002;86:428–34.
22. Knudson D, Noffal G. Time course of stretch-induced isometric strength deficits. *Eur J Appl Physiol.* 2005;94:348–51.
23. Kokkonen J, Nelson AG, Cornwell A. Acute muscle stretching inhibits maximal strength performance. *Res Q Exerc Sport.* 1998;69:411–5.
24. Maisetti O, Sastre J, Lecompte J, Portero P. Differential effects of an acute bout of passive stretching on maximal voluntary torque and the rate of torque development of the calf muscle-tendon unit. *Isokinet Exerc Sci.* 2007;15:11–7.
25. McHugh MP, Nesse M. Effect of stretching on strength loss and pain after eccentric exercise. *Med Sci Sport Exerc.* 2008;40:566–73.
26. Ogura Y, Miyahara Y, Naito H, Katamoto S, Aoki J. Duration of static stretching influences muscle force production in hamstring muscles. *J Strength Cond Res.* 2007;21:788–92.
27. Viale F, Nana-Ibrahim S, Martin RJF. Effect of active recovery on acute strength deficits induced by passive stretching. *J Strength Cond Res.* 2007;21:1233–7.
28. Young W, Elias G, Power J. Effects of static stretching volume and intensity on plantar flexor explosive force production and range of motion. *J Sports Med Phys Fitness.* 2006;46:403–11.
29. Wallmann HW, Christensen SD, Perry C, Hoover DL. The acute effects of various types of stretching static, dynamic, ballistic, and no stretch of the iliopsoas on 40-yard sprint times in recreational runners. *Int J Sports Phys Ther.* 2012;7:540–7.
30. Cè E, Longo S, Rampichini S, Devoto M, Limonta E, Venturelli M, et al. Stretch-induced changes in tension generation process and stiffness are not accompanied by alterations in muscle architecture of the middle and distal portions of the two gastrocnemii. *J Electromyogr Kinesiol.* 2015;25:469–78.
31. Herda TJ, Costa PB, Walter AA, Ryan ED, Cramer JT. The time course of the effects of constant-angle and constant-torque stretching on the muscle–tendon unit. *Scand J Med Sci Sports.* 2014;24:62–7.
32. Matsuo S, Suzuki S, Iwata M, Banno Y, Asai Y, Tsuchida W, et al. Acute effects of different stretching durations on passive torque, mobility, and isometric muscle force. *J Strength Cond Res.* 2013;27:3367–76.
33. Mizuno T, Matsumoto M, Umemura Y. Viscoelasticity of the muscle–tendon unit is returned more rapidly than range of motion after stretching. *Scand J Med Sci Sports.* 2013;23:23–30.
34. Morse CI, Degens H, Seynnes OR, Maganaris CN, Jones DA. The acute effect of stretching on the passive stiffness of the human gastrocnemius muscle tendon unit. *J Physiol.* 2008;586:97–106.
35. Nakamura M, Ikezoe T, Takeno Y, Ichihashi N. Acute and prolonged effect of static stretching on the passive stiffness of the human gastrocnemius muscle tendon unit in vivo. *J Orthop Res.* 2011;29:1759–63.
36. Ryan ED, Beck TW, Herda TJ, Hull HR, Hartman MJ, Costa PB, et al. The time course of musculotendinous stiffness responses following different durations of passive stretching. *J Orthop Sports Phys Ther.* 2008;38:632–9.
37. Ryan ED, Herda TJ, Costa PB, Defreitas JM, Beck TW, Stout J, et al. Determining the minimum number of passive stretches necessary to alter musculotendinous stiffness. *J Sports Sci.* 2009;27:957–61.
38. Bacurau RFP, Monteiro GA, Ugrinowitsch C, Tricoli V, Cabral LF, Aoki MS. Acute effect of a ballistic and a static stretching exercise bout on flexibility and maximal strength. *J Strength Cond Res.* 2009;23:304–8.
39. Ryan ED, Everett KL, Smith DB, Pollner C, Thompson BJ, Sobolewski EJ, et al. Acute effects of different volumes of dynamic stretching on vertical jump performance, flexibility and muscular endurance. *Clin Physiol Funct Imaging.* 2014;34:485–92.
40. Amiri-Khorasani M, Abu Osman NA, Yusof A. Acute effect of static and dynamic stretching on hip dynamic range of motion during instep kicking in professional soccer players. *J Strength Cond Res.* 2011;25:1647–52.

41. Herda TJ, Herda ND, Costa PB, Walter-Herda AA, Valdez AM, Cramer JT. The effects of dynamic stretching on the passive properties of the muscle-tendon unit. *J Sports Sci.* 2012;31:479–87.
42. Paradisis GP, Theodorou ASA, Pappas PT, Zacharogiannis EG, Skordilis EK, Smirniotou AS. Effects of static and dynamic stretching on sprint and jump performance in boys and girls. *J Strength Cond Res.* 2014;28:154–60.
43. Samukawa M, Hattori M, Sugama N, Takeda N. The effects of dynamic stretching on plantar flexor muscle-tendon tissue properties. *Man Ther.* 2011;16:618–22.
44. Samson M, Button DC, Chaouachi A, Behm DG. Effects of dynamic and static stretching within general and activity specific warm-up protocols. *J Sport Sci Med.* 2012;11:279–85.
45. Perrier ET, Pavol MJ, Hoffman MA. The acute effects of a warm-up including static or dynamic stretching on counter-movement jump height, reaction time, and flexibility. *J Strength Cond Res.* 2011;25:1925–31.
46. Curry BS, Chengkalath D, Crouch GJ, Romance M, Manns PJ. Acute effects of dynamic stretching, static stretching, and light aerobic activity on muscular performance in women. *J Strength Cond Res.* 2009;23:1811–9.
47. Nelson A, Kokkonen J. Acute ballistic muscle stretching inhibits maximal strength performance. *Res Q Exerc Sport.* 2001;72:415–9.
48. Beedle BB, Mann CL. A comparison of two warm-ups on joint range of motion. *J Strength Cond Res.* 2007;21:776–9.
49. Konrad A, Stafilidis S, Tilp M. Effects of acute static, ballistic, and PNF stretching exercise on the muscle and tendon tissue properties. *Scand J Med Sci Sports.* 2016;27:1070–80.
50. Zourdos MC, Wilson JM, Sommer BA, Lee S-R, Park Y-M, Henning PC, et al. Effects of dynamic stretching on energy cost and running endurance performance in trained male runners. *J Strength Cond Res.* 2012;26:335–41.
51. Su H, Chang N-J, Wu W-L, Guo L-Y, Chu I-H. Acute effects of foam rolling, static stretching, and dynamic stretching during warm-ups on muscular flexibility and strength in young adults. *J Sport Rehabil.* 2016;13:1–24.
52. Mizuno T. Changes in joint range of motion and muscle-tendon unit stiffness after varying amounts of dynamic stretching. *J Sports Sci Routledge.* 2017;35:2157–63.
53. Hough PA, Ross EZ, Howatson G. Effects of dynamic and static stretching on vertical jump performance and electromyographic activity. *J Strength Cond Res.* 2009;23:507–12.
54. Fletcher IM. The effect of different dynamic stretch velocities on jump performance. *Eur J Appl Physiol.* 2010;109:491–8.
55. Fletcher IM, Jones B. The effect of different warm-up stretch protocols on 20 meter sprint performance in trained rugby union players. *J Strength Cond Res.* 2004;18:885–8.
56. Yamaguchi T, Ishii K. Effects of static stretching for 30 seconds and dynamic stretching on leg extension power. *J Strength Cond Res.* 2005;19:677–83.
57. Turki O, Chaouachi A, Behm DG, Chtara H, Chtara M, Bishop D, et al. The effect of warm-ups incorporating different volumes of dynamic stretching on 10- and 20-m sprint performance in highly trained male athletes. *J Strength Cond Res.* 2012;26:63–72.
58. Sekir U, Arabaci R, Akova B, Kadagan SM. Acute effects of static and dynamic stretching on leg flexor and extensor isokinetic strength in elite women athletes. *Scand J Med Sci Sports.* 2010;20:268–81.
59. Byrne PJ, Kenny J, O'Rourke B. Acute potentiating effect of depth jumps on sprint performance. *J Strength Cond Res.* 2014;28:610–5.
60. Kruse NT, Barr MW, Gilders RM, Kushnick MR, Rana SR. Using a practical approach for determining the most effective stretching strategy in female college division I volleyball players. *J Strength Cond Res.* 2013;27:3060–7.
61. Leone DCPG, Pezarat P, Valamatos MJ, Fernandes O, Freitas S, Moraes AC. Upper body force production after a low-volume static and dynamic stretching. *Eur J Sport Sci.* 2014;14:69–75.
62. Pappas P, Paradisis GP, Exell TA, Smirniotou A, Tsolakis C, Arampatzis A. Acute effects of stretching on leg and vertical stiffness during treadmill running. *J Strength Cond Res.* 2017. doi:10.1519/JSC.0000000000001777.
63. Little T, Williams AG. Effects of differential stretching protocols during warm-ups on high-speed motor capacities in professional soccer players. *J Strength Cond Res.* 2006;20:203–7.
64. Gelen E. Acute effects of different warm-up methods on sprint, slalom dribbling, and penalty kick performance in soccer players. *J Strength Cond Res.* 2010;24:950–6.
65. Chatzopoulos D, Galazoulas C, Patikas D, Kotzamanidis C. Acute effects of static and dynamic stretching on balance, agility, reaction time and movement time. *J Sports Sci.* 2014;13:403–9.
66. McMillian DJ, Moore JH, Hatler BS, Taylor DC. Dynamic vs. static-stretching warm up: the effect on power and agility performance. *J Strength Cond Res.* 2006;20:492–9.
67. Haddad M, Dridi A, Chtara M, Chaouachi A, Wong DP, Behm D, et al. Static stretching can impair explosive performance for at least 24 hours. *J Strength Cond Res.* 2014;28:140–6.
68. Duncan MJ, Woodfield LA. Acute effects of warm up protocol on flexibility and vertical jump in children. *J Exerc Physiol.* 2006;9:9–16.
69. Van Gelder LH, Bartz SD. The effect of acute stretching on agility performance. *J Strength Cond Res.* 2011;25:3014–21.
70. Fattahi-Bafghi A, Amiri-Khorasani M. Sustaining effect of different stretching methods on power and agility after warm-up exercise in soccer players. *World Appl Sci J.* 2013;21:520–5.
71. Werstein KM, Lund RJ. The effects of two stretching protocols on the reactive strength index in female soccer and rugby players. *J Strength Cond Res.* 2012;26:1564–7.
72. Fletcher IM, Monte-Colombo MM. An investigation into the effects of different warm-up modalities on specific motor skills related to soccer performance. *J Strength Cond Res.* 2010;24:2096–101.
73. Pearce AJ, Kidgell DJ, Zois J, Carlson JS. Effects of secondary warm up following stretching. *Eur J Appl Physiol.* 2009;105:175–83 (**Springer-Verlag**).
74. Manoel ME, Harris-Love MO, Danoff JV, Miller TA. Acute effects of static, dynamic, and proprioceptive neuromuscular facilitation stretching on muscle power in women. *J Strength Cond Res.* 2008;22:1528–34.
75. Holt BW, Lambourne K. The impact of different warm-up protocols on vertical jump performance in male collegiate athletes. *J Strength Cond Res.* 2008;22:226–9.
76. Fletcher IM, Anness R. The acute effects of combined static and dynamic stretch protocols on fifty-meter sprint performance in track-and-field athletes. *J Strength Cond Res.* 2007;21:784–7.
77. Faigenbaum AD, McFarland JE, Schwerdtman JA, Ratamess NA, Kang J, Hoffman JR. Dynamic warm-up protocols, with and without a weighted vest, and fitness performance in high school female athletes. *J Athl Train.* 2006;41:357–63.
78. Faigenbaum AD, Bellucci M, Bernieri A, Bakker B, Hoorens K. Acute effects of different warm-up protocols on fitness performance in children. *J Strength Cond Res.* 2005;19:376–81.
79. Carvalho FLP, Carvalho MCGA, Simão R, Gomes TM, Costa PB, Neto LB, et al. Acute effects of a warm-up including active, passive, and dynamic stretching on vertical jump performance. *J Strength Cond Res.* 2012;26:2447–52.
80. Morrin N, Redding E. Acute effects of warm-up stretch protocols on balance, vertical jump height, and range of motion in dancers. *J Dance Med Sci.* 2013;17:34–40.

81. Needham RA, Morse CI, Degens H. The acute effect of different warm-up protocols on anaerobic performance in elite youth soccer players. *J Strength Cond Res.* 2009;23:2614–20.
82. Taylor K-L, Sheppard JM, Lee H, Plummer N. Negative effect of static stretching restored when combined with a sport specific warm-up component. *J Sci Med Sport.* 2009;12:657–61.
83. Amiri-Khorasani M, Calleja-Gonzalez J, Mogharabi-Manzari M. Acute effect of different combined stretching methods on acceleration and speed in soccer players. *J Hum Kinet.* 2016;50:179–86.
84. Franco BL, Signorelli GR, Trajano GS, Costa PB, de Oliveira CG. Acute effects of three different stretching protocols on the wingate test performance. *J Sports Sci Med.* 2012;11:1–7.
85. Fattahi-Bafghi A, Amiri-Khorasani M. Effects of static and dynamic stretching during warm-up on vertical jump in Soccer players. *Int J Sport Stud.* 2012;2:484–8.
86. Sá MA, Neto GR, Costa PB, Gomes TM, Bentes CM, Brown AF, et al. Acute effects of different stretching techniques on the number of repetitions in a single lower body resistance training session. *J Hum Kinet.* 2015;45:177–85.
87. Ayala F, Moreno-Pérez V, Vera-García FJ, Moya M, Sanz-Rivas D, Fernandez-Fernandez J. Acute and time-course effects of traditional and dynamic warm-up routines in young elite junior tennis players. *PLoS One.* 2016;11:1–14 (**Sampaio J, editor; Routledge Academic**).
88. Alemdaroglu U, Köklü Y, Koz M. The acute effect of different stretching methods on sprint performance in taekwondo practitioners. *J Sports Med Phys Fitness.* 2017;57:1104–10.
89. Costa PB, Herda TJ, Herda AA, Cramer JT. Effects of dynamic stretching on strength, muscle imbalance, and muscle activation. *Med Sci Sport Exerc.* 2014;46:586–93.
90. Samuel MN, Holcomb WR, Guadagnoli MA, Rubley MD, Wallmann H. Acute effects of static and ballistic stretching on measures of strength and power. *J Strength Cond Res.* 2008;22:1422–8.
91. Behm DG, Blazevich AJ, Kay AD, McHugh M. Acute effects of muscle stretching on physical performance, range of motion, and injury incidence in healthy active individuals: a systematic review. *Appl Physiol Nutr Metab.* 2016;41:1–11.
92. Unick J, Kieffer HS, Cheesman W, Feeney A. The acute effects of static and ballistic stretching on vertical jump performance in trained women. *J Strength Cond Res.* 2005;19:206–12.
93. Bandy WD, Irion JM, Briggler M. The effect of static stretch and dynamic range of motion training on the flexibility of the hamstring muscles. *J Orthop Sports Phys Ther.* 1998;27:295–300.
94. Alter MJ. *Sports Stretch.* Champaign, IL: Human Kinetics; 1997.
95. Jagers JR, Swank AM, Frost KL, Lee CD. The acute effects of dynamic and ballistic stretching on vertical jump height, force, and power. *J Strength Cond Res.* 2008;22:1844–9.
96. Smith CA. The warm-up procedure: to stretch or not to stretch. A brief review. *J Orthop Sports Phys Ther.* 1994;19:12–7.
97. Yamaguchi T, Ishii K. An optimal protocol for dynamic stretching to improve explosive performance. *J Phys Fit Sport Med.* 2014;3:121–9.
98. Cohen J. *Statistical power analysis for the behavioural sciences.* Stat Power Anal Behav Sci. 1988;L. Erbaum:14–68.
99. Murphy JC, Nagle E, Robertson RJ, Mccrory JL. Effect of single set dynamic and static stretching exercise on jump height in college age recreational athletes. *Int J Exerc Sci.* 2010;3:214–24.
100. Behm DG, Plewe S, Grage P, Rabbani A, Beigi HT, Byrne JM, et al. Relative static stretch-induced impairments and dynamic stretch-induced enhancements are similar in young and middle-aged men. *Appl Physiol Nutr Metab.* 2011;36:790–7.
101. Barroso R, Tricoli V, dos Santos Gil S, Ugrinowitsch C, Roschel H. Maximal strength, number of repetitions, and total volume are differently affected by static-, ballistic-, and proprioceptive neuromuscular facilitation stretching. *J Strength Cond Res.* 2012;26:2432–7.
102. Aguilar AJ, DiStefano LJ, Brown CN, Herman DC, Guskiewicz KM, Padua DA. A dynamic warm-up model increases quadriceps strength and hamstring flexibility. *J Strength Cond Res.* 2012;26:1130–41.
103. Hayes PR, Walker A. Pre-exercise stretching does not impact upon running economy. *J Strength Cond Res.* 2007;21:1227–32.
104. O'Sullivan K, Murray E, Sainsbury D. The effect of warm-up, static stretching and dynamic stretching on hamstring flexibility in previously injured subjects. *BMC Musculoskelet Disord.* 2009;10:37.
105. Magnusson SP, Simonsen EB, Dyhre-Poulsen P, Aagaard P, Mohr T, Kjaer M. Viscoelastic stress relaxation during static stretch in human skeletal muscle in the absence of EMG activity. *Scand J Med Sci Sports.* 1996;6:323–8.
106. Magnusson SP, Simonsen EB, Aagaard P, Gleim GW, McHugh MP, Kjaer M. Viscoelastic response to repeated static stretching in the human hamstring muscle. *Scand J Med Sci Sports.* 1995;5:342–7.
107. Kubo K, Kanehisa H, Kawakami Y, Fukunaga T. Influence of static stretching on viscoelastic properties of human tendon structures in vivo. *J Appl Physiol.* 2001;90:520–7.
108. Fletcher IM, Monte-Colombo MM. An investigation into the possible physiological mechanisms associated with changes in performance related to acute responses to different preactivity stretch modalities. *Appl Physiol Nutr Metab.* 2010;35:27–34.
109. Herda TJ, Cramer JTJ, Ryan EED, McHugh MP, Stout JJR. Acute effects of static versus dynamic stretching on isometric peak torque, electromyography, and mechanomyography of the biceps femoris muscle. *J Strength Cond Res.* 2008;22:809–17.
110. Bishop D. Warm up I. *Sport Med.* 2003;33:439–54.
111. Mahieu NN, McNair P, De Muynck M, Stevens V, Blanckaert I, Smits N, et al. Effect of static and ballistic stretching on the muscle-tendon tissue properties. *Med Sci Sport Exerc.* 2007;39:494–501.
112. Guissard N, Duchateau J, Hainaut K. Muscle stretching and motoneuron excitability. *Eur J Appl Physiol.* 1988;58:47–52.
113. Bradley PS, Olsen PD, Portas MD. The effect of static, ballistic, and proprioceptive neuromuscular facilitation stretching on vertical jump performance. *J Strength Cond Res.* 2007;21:223–6.
114. Torres EM, Kraemer WJ, Vingren JL, Volek JS, Hatfield DL, Spiering BA, et al. Effects of stretching on upper-body muscular performance. *J Strength Cond Res.* 2008;22:1279–85.
115. Christensen BK, Nordstrom BJ. The effects of proprioceptive neuromuscular facilitation and dynamic stretching techniques on vertical jump performance. *J Strength Cond Res.* 2008;22:1826–31.
116. Siatras T, Papadopoulos G, Mameletzi D, Gerodimos V, Kellis S. Static and dynamic acute stretching effect on gymnasts' speed in vaulting. *Pediatr Exerc Sci.* 2003;15:383–91.
117. Dalrymple KJ, Davis SE, Dwyer GB, Moir GL. Effect of static and dynamic stretching on vertical jump performance in collegiate women volleyball players. *J Strength Cond Res.* 2010;24:149–55.
118. Pagaduan JC, Pojskić H, Užičanin E, Babajić F. Effect of various warm-up protocols on jump performance in college football players. *J Hum Kinet.* 2012;35:127–32.
119. Ayala F, De Ste Croix M, Sainz De Baranda P, Santonja F. Acute effects of static and dynamic stretching on hamstring eccentric isokinetic strength and unilateral hamstring to quadriceps strength ratios. *J Sports Sci.* 2013;31:831–9.
120. Kendall BJ. The acute effects of static stretching compared to dynamic stretching with and without an active warm up on anaerobic performance. *Int J Exerc Sci.* 2017;10:53–61.

121. Clark L, O'Leary CB, Hong J, Lockard M. The acute effects of stretching on presynaptic inhibition and peak power. *J Sports Med Phys Fitness*. 2014;54:605–10.
122. Chatzopoulos DE, Yiannakos A, Kotzamanidou M, Bassa E. Warm-up protocols for high school students. *Percept Mot Skills*. 2015;121:1–13.
123. Vetter RE. Effects of six warm-up protocols on sprint and jump performance. *J Strength Cond Res*. 2007;21:819–23.
124. Beedle B, Rytter SJ, Healy RC, Ward TR. Pretesting static and dynamic stretching does not affect maximal strength. *J Strength Cond Res*. 2008;22:1838–43.
125. Turki O, Chaouachi A, Drinkwater EJ, Chtara M, Chamari K, Amri M, et al. Ten minutes of dynamic stretching is sufficient to potentiate vertical jump performance characteristics. *J Strength Cond Res*. 2011;25:2453–63.
126. Papadopoulos G, Siatras T, Kellis S. The effect of static and dynamic stretching exercises on the maximal isokinetic strength of the knee extensors and flexors. *Isokinet Exerc Sci*. 2005;13:285–91.
127. Knudson D, Bennett K, Corn R, Leick D, Smith C. Acute effects of stretching are not evident in the kinematics of the vertical jump. *J Strength Cond Res*. 2001;15:98–101.
128. Mizuno T, Umemura Y. Dynamic stretching does not change the stiffness of the muscle–tendon unit. *Int J Sports Med*. 2016;37:1044–50.
129. Yamaguchi T, Takizawa K, Shibata K. Acute effect of dynamic stretching on endurance running performance in well-trained male runners. *J Strength Cond Res*. 2015;29:3045–52.
130. Weerapong P, Hume PA, Kolt GS. Stretching: mechanisms and benefits for sport performance and injury prevention. *Phys Ther Rev Taylor Francis*. 2004;9:189–206.
131. Taylor DC, Dalton JD, Seaber AV, Garrett WE. Viscoelastic properties of muscle–tendon units. The biomechanical effects of stretching. *Am J Sports Med*. 1990;18:300–9.
132. Kubo K, Kanehisa H, Fukunaga T. Gender differences in the viscoelastic properties of tendon structures. *Eur J Appl Physiol*. 2003;88:520–6.
133. Riemann BL, DeMont RG, Ryu K, Lephart SM. The effects of sex, joint angle, and the gastrocnemius muscle on passive ankle joint complex stiffness. *J Athl Train*. 2001;36:369–75 (**National Athletic Trainers Association**).
134. Magnusson SP. Passive properties of human skeletal muscle during stretch maneuvers. *Scand J Med Sci Sports*. 1998;8:65–77 (**Blackwell Publishing Ltd**).
135. Handrakis JP, Southard VN, Abreu JM, Aloisa M, Doyen MR, Echevarria LM, et al. Static stretching does not impair performance in active middle-aged adults. *J Strength Cond Res*. 2010;24:825–30.
136. Egan AD, Cramer JT, Massey LL, Marek SM. Acute effects of static stretching on peak torque and mean power output in national collegiate athletic association division I women's basketball player. *J Strength Cond Res*. 2006;20:778–82.
137. Chaouachi A, Castagna C, Chtara M, Brughelli M, Turki O, Galy O, et al. Effect of warm-ups involving static or dynamic stretching on agility, sprinting, and jumping performance in trained individuals. *J Strength Cond Res*. 2010;24:2001–11.
138. Babault N, Bazine W, Deley G, Paizis C, Lattier G. Direct relation of acute effects of static stretching on isokinetic torque production with initial flexibility level. *Int J Sports Physiol Perform*. 2015;10:117–9.
139. Hirata K, Miyamoto-Mikami E, Kanehisa H, Miyamoto N. Muscle-specific acute changes in passive stiffness of human triceps surae after stretching. *Eur J Appl Physiol*. 2016;116:911–8.
140. Bouvier T, Opplert J, Cometti C, Babault N. Acute effects of static stretching on muscle–tendon mechanics of quadriceps and plantar flexor muscles. *Eur J Appl Physiol*. 2017;117:1309–15.
141. Lima CD, Brown LE, Wong MA, Leyva WD, Pinto RS, Cadore EL, et al. Acute effects of static vs. ballistic stretching on strength and muscular fatigue between ballet dancers and resistance-trained women. *J Strength Cond Res*. 2016;30:3220–7.
142. Moran DS, Mendal L. Core temperature measurement: methods and current insights. *Sports Med*. 2002;32:879–85.
143. Buchthal F, Kaiser E, Knappeis GG. Elasticity, viscosity and plasticity in the cross striated muscle fibre. *Acta Physiol Scand*. 1944;8:16–37.
144. Gajdosik RL. Passive extensibility of skeletal muscle: review of the literature with clinical implications. *Clin Biomech*. 2001;16:87–101.
145. Magnusson SP, Simonsen EB, Aagaard P, Boesen J, Johannsen F, Kjaer M. Determinants of musculoskeletal flexibility: viscoelastic properties, cross-sectional area, EMG and stretch tolerance. *Scand J Med Sci Sports*. 1997;7:195–202.
146. Nordez A, Cornu C, McNair P. Acute effects of static stretching on passive stiffness of the hamstring muscles calculated using different mathematical models. *Clin Biomech*. 2006;21:755–60.
147. Nordez A, McNair PJ, Casari P, Cornu C. The effect of angular velocity and cycle on the dissipative properties of the knee during passive cyclic stretching: a matter of viscosity or solid friction. *Clin Biomech*. 2009;24:77–81.
148. Blazeovich AJ, Cannavan D, Waugh CM, Fath F, Miller SC, Kay AD. Neuromuscular factors influencing the maximum stretch limit of the human plantar flexors. *J Appl Physiol*. 2012;113:1446–55.
149. Abellana S, Guissard N, Duchateau J. The relative lengthening of the myotendinous structures in the medial gastrocnemius during passive stretching differs among individuals. *J Appl Physiol*. 2009;106:169–77.
150. Tillin NA, Bishop D. Factors modulating post-activation potentiation and its effect on performance of subsequent explosive activities. *Sports Med*. 2009;39:147–66.
151. Sale DG. Postactivation potentiation: role in human performance. *Exerc Sport Sci Rev*. 2002;30:138–43.
152. Maloney SJ, Turner AN, Fletcher IM. Ballistic exercise as a pre-activation stimulus: a review of the literature and practical applications. *Sports Med*. 2014;44:1347–59.
153. Henneman E, Somjen G, David A. Excitability and inhibibility of motoneurons of different sizes. *J Neurophysiol*. 1965;28:599–620.
154. Baudry S, Duchateau J. Postactivation potentiation in a human muscle: effect on the rate of torque development of tetanic and voluntary isometric contractions. *J Appl Physiol*. 2007;102:1394–401.
155. Cè E, Rampichini S, Maggioni MA, Veicsteinas A, Merati G. Effects of passive stretching on post-activation potentiation and fibre conduction velocity of biceps brachii muscle. *Sport Sci Health*. 2009;4:43–50.
156. Sweeney HL, Bowman BF, Stull JT. Myosin light chain phosphorylation in vertebrate striated muscle: regulation and function. *Am J Physiol Cell Physiol*. 1993;264:1085–95.
157. Rassier DE, MacIntosh BR. Coexistence of potentiation and fatigue in skeletal muscle. *Brazilian J Med Biol Res*. 2000;33:499–508.
158. Yamaguchi T, Ishii K, Yamanaka M, Yasuda K. Acute effects of dynamic stretching exercise on power output during concentric dynamic constant external resistance leg extension. *J Strength Cond Res*. 2007;21:1238–44.
159. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Neural adaptation to resistance training: changes in evoked V-wave and H-reflex responses. *J Appl Physiol*. 2002;92:2309–18.
160. Zehr EP. Considerations for use of the Hoffmann reflex in exercise studies. *Eur J Appl Physiol*. 2002;86:455–68.

161. Vujnovich AL, Dawson NJ. The effect of therapeutic muscle stretch on neural processing. *J Orthop Sport Phys Ther.* 1994;20:145–53.
162. Burke D, Hagbarth KE, Löfstedt L. Muscle spindle activity in man during shortening and lengthening contractions. *J Physiol.* 1978;277:131–42.
163. Fetz EE, Jankowska E, Johannisson T, Lipski J. Autogenetic inhibition of motoneurons by impulses in group Ia muscle spindle afferents. *J Physiol.* 1979;293:173–95.
164. Guissard N, Duchateau J, Hainaut K. Mechanisms of decreased motoneurone excitation during passive muscle stretching. *Exp Brain Res.* 2001;137:163–9.
165. Coxon JP, Stinear JW, Byblow WD. Amplitude of muscle stretch modulates corticomotor gain during passive movement. *Brain Res.* 2005;1031:109–17.