ADDENDUM

THE ACUTE EFFECTS OF STRETCHING ON STRENGTH, SPEED, POWER & MUSCULAR ENDURANCE PRODUCTION: A NARRATIVE REVIEW OF PUBLISHED RESEARCH BETWEEN 2011 AND 2020

PREAMBLE

The present thesis constitutes a research investigation conducted in the mid 2000's to primarily answer the question 'does realistic short-duration stretching – as commonly performed in 'real world' exercise and training situations – impair performance'. Based on the literature performed on this topic *circa* the early 2000's, the answer would be clear and resounding 'yes it does', and, as such, recommendations have been to avoid any form of stretching in the warm-up period for any activity involving muscular performance (Shrier, I., 2004).

Close scrutiny of the literature would reveal that the stretching methods used in the vast majority of the studies are of durations and intensities not commonly used by coaches, athletes and those in the fitness industry. Furthermore, researchers in this era commonly confused a 'general warm-up' with a 'specific warm-up' (Kay and Blazevich, 2012) and thus an activity designed to improve range of motion became an isolated and solely used warm-up prior to muscular performance. Thus, a realistic appraisal of stretching's effect on various indices of muscular performance was warranted and the present study undertaken.

Subsequently, the study was designed, data collected and analysed, and the thesis completed and submitted to the primary supervisor for final comments, feedback and examination in 2011. Due to a series of egregious events that could be described as comical, if not tragic for the student, the final thesis was not actually submitted for examination until 2020, a full 9 years after the initial 'completion'. Accordingly, the thesis reflects (1) an investigation aimed at answering a question in exercise science that existed in the mid 2000's and, as a corollary, (2) the inclusion of comparable literature up until the submission in 2011.

The aim of this literature review, then, has been to (1) briefly summarise the previous literature findings, (2) review the conclusions of the present study, (3) provide a narrative review of the current literature of the last decade, thereby providing a link between the original thesis material and the recent developments not included previously, and (4) proffer a historical perspective of pre-2011 literature *vis a vis* current studies and, in particular, the findings of the present thesis.

INTRODUCTION

Asking the question 'what is the ideal way to structure a warm-up before various muscular contraction performance' does not have a clear answer. Historical tradition would have a warm-up comprising a general aerobic component, some form of stretching, followed by specific replication of the movements or activities about to be performed (Bishop 2003). This wisdom began to be questioned in the late 1990's, when a number of studies were published demonstrating that stretching in general, and static stretching in particular, had deleterious effects on subsequent muscular contractile properties, such as maximal strength and power production (Kokkonen et al., 1998; Fowles et al., 2000).

Early research in this field saw a number of studies demonstrating that stretching had a negative effect on performance when testing tasks to assess strength (Behm et al., 2001), speed (Fletcher and Jones, 2004) and power (Church et al., 2001) had stretching performed immediately prior. These findings laid the foundation for the practice of avoiding pre-exercise stretching both in the sports and fitness populations (Malek and Coburn, 2011) and academia (Behm 2018). The early research subsequently set the parameters for a continuation of studies in this area, where research the decade of the 2000's saw a large body of evidence that cautioned against the inclusion of stretching in the warm-up period, as studies had shown that stretching impaired maximal force or torque production, power production and vertical jump performance (Church et al., 2001; Cornwell et al., 2001), running velocity and speed of movement (Nelson et al., 2005;) and muscle activation (Behm et al., 2001; Fowles and Sale, 1997).

By 2006, the European College of Sport Sciences published a position statement concluding that there was firm evidence that an acute bout of stretching could negatively affect performance in muscular tests requiring maximal force (Magnusson and Renstrom, 2006). Four years later, the American College of Sports Medicine's guidelines (ACSM, 2010; Gerber et al., 2011) followed the European College and changed their recommendations and removed static stretching as part of a warm-up routine and only included cardiovascular work when strength or power was important to performance.

Scrutiny of the literature published in this era reveals disparity in the effects of stretching on performance. A consistent detrimental effect of stretching was never convincingly demonstrated. Rather, a clear dose-response relationship between stretching duration and the impairment in performance was identified (Behm and Chaouachi, 2011; Kay and Blazevich 2012). The majority of studies reported negative relationships between stretching and jumping performance (Table 1) and force production (Table 2). The studies either used stretching durations not typically used in athletic or fitness settings. Or used isolated stretching as the sole means of a warm-up, with no specific movement rehearsal of the performance tasks.

Examining the methodology of the literature indicated that only seven studies investigated a total stretching duration of ~30 seconds (Table 3). This is surprising, given that this short style of stretching is commonly and routinely used in the athletic, fitness and special population settings. Short duration stretching would normally be considered as part of a comprehensive warm-up, where the goal is preparation for muscular performance and not maximal flexibility development.

Table 1. Effect of Stretching on Jump Performance

Reference	n	Stretch duration per muscle	Stretch intensity	Effect and percentage change	Effect size
Behm et al. (2006)	18	3 x 30 s	POD	No effect on jump height but increased contact time by 5.4%	0.47
Bradley et al. (2007)	18	4 x 30 s	<POD	↓ vertical jump 4.0%	0.62
Cornwell et al. (2002)	16	90 s stretch of quadriceps and gluteals	NR	↓ concentric jump ↓ drop jump	NA
Fletcher and Monte-Colombo (2010)	21	2 x 15 s	<POD	↓ countermovement jump 3.7% ↓ drop jump 4.8%	0.37 0.49
Gonzalez-Rave et al. (2009)	24	3 stretches of 3 reps x 15 s CMJ 3 stretches of 3 reps x 15 s SJ	<POD	No effect on jump height 3.1% (CMJ) 11.11% (SJ)	0.25 0.75
Holt and Lambourne (2008)	64	3 x 5 s	POD	↓ vertical jump	NA
Hough et al. (2009)	11	1 x 30 s	<POD	↓ vertical jump 1.7%	0.11
Knudson et al. (2001)	20	3 x 15 s	<POD	No sig effect on jump height 0.4%	0.02
Power et al. (2004)	12	3 x 45 s	POD	No effect on jump height 14.3%	1.00
Robbins and Scheuermann (2008)	20	2 x 15 s 4 x 15 s 6 x 15 s	POD POD POD	↓ vertical jump 0.8% ↓ vertical jump 2.2% ↓ vertical jump 3.2%	0.20 0.58 0.85
Samuel et al. (2008)	24	3 x 30 s	<POD	No sig effect on jump height	NA
Vetter (2007)	12	2 x 30 s (women)	NR	↓ vertical jump 0.35%	0.08
Vetter (2007)	14	2 x 30 s (men)	NR	↓ vertical jump 0.9%	0.25
Wallman et al. (2005)	14	3 x 30 s	<POD	↓ vertical jump 5.6%	0.84
Young and Elliott (2001)	14	3 x 15 s	POD	↓ drop jump	NA

POD, point of discomfort; NR, not reported; NA, not available

Table 2. Effect of Stretching on Force Production.

Reference	n	Stretch duration per muscle	Stretch intensity	Effect and percentage change	Effect size
Brandenburg et al. (2006)	16	2 hamstrings stretches x 3 reps x 15 s 2 hamstrings stretches x 3 reps x 15 s	NR	↓ concentric torque 2.8% ↓ concentric torque 3.4%	0.12 0.13
Cramer et al. (2004)	21	4 sets of 4 stretches x 30 s	<POD	↓ leg isokinetic peak torque 2.7%	0.51
Cramer et al. (2006)	21	4 sets of 4 stretches x 30 s at 60os-1 4 sets of 4 stretches x 30 s at 180 s-1	<POD <POD	↓ leg isokinetic peak torque 1.1% ↓ leg isokinetic peak torque 6.5%	0.17 0.86
Cramer et al. (2007)	15	4 sets of 4 stretches x 30 s at 60os-1 4 sets of 4 stretches x 30 s at 180 s-1	<POD <POD	↓ leg isokinetic peak torque 2.6% ↓ leg isokinetic peak torque 1.8%	0.14 0.08
Marek et al. (2005)	19	4 reps x 30 s at 60os-1 4 reps x 30 s at 300 s-1	POD POD	↓ leg isokinetic torque 0.4% ↓ leg isokinetic torque 2.6%	0.05 0.26
Nelson et al. (2001)	15	4 stretches x 4 reps x 30 assisted or unassisted	Assisted POD Unassisted NR	↓ leg isokinetic torque at slower angular velocities, but not higher angular velocities 7.2%	NA
Siatras et al. (2008)	50	1 x 10, 20, 30 or 60 s	POD	↓ leg isokinetic torque only after 30 and 60 s stretches	NA
Yamaguchi et al. (2006)	12	6 stretches of 4 sets x 30 s at 5% MVC	POD	↓ leg extension power 10.8%	0.47
Yamaguchi et al. (2006)	12	6 stretches of 4 sets x 30 s at 30% MVC	POD	↓ leg extension power 3.7%	0.25
Yamaguchi et al. (2006)	12	6 stretches of 4 sets x 30 s at 60% MVC	POD	↓ leg extension power 10.6%	0.56
Zakas et al. (2005)	14	1 x 30 s 10 x 30 s 16 x 30 s	<POD <POD <POD	No sig change ↓ isokinetic torque 3.3% ↓ isokinetic torque 2.8%	0.78 0.86 0.79
Zakas et al. (2006)	16	3 reps x 15 s vs. 20 x 15 s-300 s-1 3 reps x 15 s vs. 20 x 15 s-600 s-1 3 reps x 15 s vs. 20 x 15 s-1200 s-1 3 reps x 15 s vs. 20 x 15 s-1800 s-1 3 reps x 15 s vs. 20 x 15 s-3000 s-1	<POD <POD <POD <POD <POD	↓ isokinetic torque 5.2% ↓ isokinetic torque 5.4% ↓ isokinetic torque 8.4% ↓ isokinetic torque 6.5% ↓ isokinetic torque 12.9%	0.32 0.36 0.60 0.47 0.89

POD, point of discomfort; NR, not reported; NA, not available.

There were equivocal findings from studies published in the decade of the 2000's. As reported in Table 1, nine studies did not demonstrate any significant reduction in performance. Five reported no change in power development or speed-oriented tasks including 20-m sprint time (Beckett et al. 2009; Church et al., 2001; Holt et al., 2008; Murphy et al., 2010; McMillian et al., 2006). One investigation reported a significant increase in five-step jump distance (McMillian et al. 2006). Three studies reported no significant reductions in maximal strength, including isometric plantar flexor maximum voluntary contraction (Kay and Blazevich, 2008), handgrip strength (Knudson and Noffal, 2005) or knee extension maximal strength (Siatras et al., 2008). Only one study found a small but significant impairment in 20-metre sprint velocity (Fletcher and Jones, 2004). However, this finding was not replicated when studied several years later by Beckett et al. (2009), who found no effect of stretching on sprint times. A possible explanation for the disparity is due to the stretching timing within the session. Beckett et al. (2009) applied static stretching between the change of direction sprints and previous studies showing performance impairments (Fletcher and Jones 2004) performed the static stretching immediately prior to the sprint testing. This might suggest that the smaller dose of stretching in combination with high-intensity muscular performance activities might mitigate the negative effects stretching appears to exert on sprinting.

When taken *in toto*, the data from these studies demonstrate that the commonly used short durations of stretching around 30-seconds, *contra* guidelines from the ECSS (2006) and the ACSM (2010), do not create in a meaningful reduction in muscular performance. Similarly, contemporaneous literature examining the effect of slightly longer stretching durations ~45-seconds demonstrates mixed findings: while some studies report significant losses in lower limb muscle groups, other investigations did not, making firm recommendations to avoid pre-exercise stretching impossible. In a review of the literature, Kay and Blazevich (2012) observed that overall, 50% of the findings showed that no detrimental effect on strength was likely when stretch duration was 30–45 seconds, with the pooled estimate of the changes reported ~4.2%, which is well within the normal variability for maximum voluntary performance, and of no relevant meaning in most training and performance settings.

Table 3: Investigations using a total stretch time ~30-seconds

Reference	n	Stretch duration per muscle	Stretch intensity	Effect and percentage change	Effect size
Beckett et al. (2009)	12	1 x 20 s	<POD	20 − m sprint COD No sig change	0.87
Holt and Lambourne (2008)	64	3 x 5 s	POD	No sig change vertical jump	NA
McMillian et al. (2006)	30	1 x 20-30 s	<POD	No sig change T shuttle run 5-step jump Med ball throw	NA
Murphy et al. (2010)	42	1 x 20 s	POD	No sig change Vertical jump	0.42
Church et al. (2001)	40	1 x 30 s	POD	No sig change Vert jump	NA
Knudson et al. (2001)	20	3 x 15 s	<POD	No sig effect on jump height 0.4%	0.02
Siatras et al. (2008)	50	1 x 10, 20, 30 or 60 s	POD	↓ leg isokinetic torque only after 30 and 60 s stretches	NA

POD, point of discomfort; NR, not reported; NA, not available

When considering the present thesis, the investigation was conducted in this environment, when a number of research groups were attempting to establish if stretching, when performed as part of a warm-up typically used in the real world had an effect – positive or negative – on subsequent performance, as it had been identified that the studies reporting negative effects used methodologies inconsistent with those used in the athletic and fitness environments (ECSS, 2006; ACSM 2010).

BRIEF SUMMARY OF THE PREVIOUS LITERATURE UP TO 2011

In its varying forms - static, PNF, dynamic – stretching, when included as part of the warm-up period prior to strength and power performance tasks, has been widely criticized in reviews published between 2000 and 2011 (Pope et al., 2000; Shrier, 2004; McHugh and Cosgrave, 2010;). In support of this position is the non-trivial body of evidence that has cautioned against the use of stretching immediately before performance of activities requiring strength, speed and power production (Shrier, 2004; McHugh and Cosgrave, 2010; Simic et al., 2013; Peck et al., 2014).

A number of studies have reported detrimental effects on strength, speed and power production when preceded by acute stretching. One study examined the acute effects of static stretching of the plantar flexors on maximal strength (Fowles et al. 2000). The investigators had the participants subjects perform 13 sets of 135 seconds each with a total of 30 minutes of time under stretch on the calf muscles. A significant decrease in maximal isometric voluntary contraction immediately post (28%) and at 5 (21%), 15 (13%), 30 (12%), 45 (10%), and 60 (9%) minutes after stretching. Whilst physiologically interesting, this duration of stretching is at odds with a routine warm-up. Therefore, can hardly be used as evidence to not stretch prior to strength performance, as it has for many years.

Similarly, a study by Behm and Kibele (2007) reported the effects of two minutes total stretching duration on the lower limb muscles and found a significant decrement in jump height (3.5%) when the power assessment was performed immediately after the stretching. Other studies have reported similar findings on maximal force production when preceded immediately by static stretching (Fowles et al. 2000). The first decade of this century saw a vast number of investigations reporting negative effects of stretching on various indices of muscular performance (Table 1).

Accordingly, systematic literature and meta-analytical reviews published in this era caution against the use of stretching in the warm-up routine. For example, Shrier (2004) concluded that stretching is harmful to subsequent strength and power actions and should be avoided. In the most comprehensive review of this period, Behm and Chaouachi (2011) concluded that there is a large body of evidence that has found static stretching impairs subsequent performance. Simic et al. (2013) published a meta-analytical review which included 104 studies examining the effects of pre-exercise stretching on indices of muscle strength, speed and power in both trained and untrained populations up to the period of 2010. The review reported an average stretch duration per muscle group between 86–314 seconds. The authors reported that stretching negatively affected maximal strength (5.4%) and power (1.9%) performances, irrespective of the participant’s age, gender, or fitness level.

Reading of this literature without examining the specific methodology employed by each team of investigators, may lead to conclusions and recommendations about the effects of stretching on performance using stretching methods at variance to those used in the field. For example, a summary article in the NSCA Journal by Stone et al. (2006) cautions practitioners from using stretching in the warm-up period, stating that though acute stretching, as part of a warm-up, can enhance range of motion, it may also reduce performance, as acute stretching has been demonstrated to reduce peak force, rate of force production, and power output.

Evidence of this perspective is the conclusions of Simic et al. (2013) who recommended the avoidance of stretching during the warm-up routine. As mentioned previously, blanket statements that display a superficial reading of the literature and conflate stretching *per se* with stretching that can be performed at varying durations and intensities as part of a comprehensive warm-ups can be seen in the position statement issued by the European College of Sport Sciences (Magnusson and Renström, 2006). Here, the authors conclude that there is ample evidence to discourage the use of static stretching before activities that require maximal efforts (e.g., maximal strength-, power-related tasks such as jumping). Moreover, guidelines from the American College of Sports Medicine echo these recommendations to discontinue the inclusion of stretching as part of the warm-up routine (Garber et al., 2011).

KEY FINDINGS OF PRESENT RESEARCH STUDY

Numerous studies have investigated the acute effects of various modes of stretching and flexibility exercises on indices of muscular effort and performance, such as speed, strength and power (Rubini et al. 2007; Behm and Chaouachi, 2011). Early investigations generally found that augmentation of flexibility prior to muscular effort resulted in performance decrements (Young 2007).

However, the practical application to sport and exercise of the many studies showing deleterious effects of stretching on performance have been recently questioned, primarily due to restrictive participant number, excessive stretching durations, lack of multiple treatment groups to assess the impact of varied stretching methods on several measurements of muscular performance and insufficient time period between stretching and testing protocols (Behm and Chaouachi, 2011).

The current study was designed and implemented to address the short comings in the literature, assessing the impact of several stretching and warm-up methods typically used in sport and exercise training settings on the motor functions of strength, speed and power. In a cohort of trained sixty individuals, contrary to the major of studies published at that time, there was no significant difference found between treatment groups and the indices of muscular performance when stretching was conducted in a tolerable, short-duration manner typically used in 'real world' sports and fitness settings.

CONTEMPORY LITERATURE REVIEW: 2011 TO 2020

METHODS

This narrative review included studies that examined the acute effects of stretching on subsequent indices of strength, speed, power and muscular-endurance performances. An electronic literature search was conducted in the following databases: PubMed, Medline, ScienceDirect, and Google Scholar between the years 2011 and 2020. Search terms included the key words, either separately or combined: stretching, static stretching, PNF, dynamic stretching, active stretching, warm-ups, physical performance, strength, power, speed and muscular-endurance.

INCLUSION CRITERIA

Only studies that fulfilled the following inclusion criteria were included in this review: (1) the study addressed a research question related to the acute effects of stretching on strength, speed, power and muscular-endurance performances and (2) included healthy active or competitive adults (studies conducted with children and seniors were excluded); (3) the main outcome was a performance measure; and (4) original trials written in English and published in a peer-reviewed journal. Extraction and evaluation of the literature based on this inclusion criteria revealed sixteen eligible studies for analysis. In addition to the sixteen original investigations, several narrative and systematic reviews, and meta-analyses have been published this last decade examining the acute effects of stretching on tasks requiring muscular strength, speed and power (Kay and Blazevich, 2012; Behm et al., 2016; Opplert and Babault, 2018; Lima et al., 2019; Chaabene et al., 2019).

Prior to 2011, the majority of studies had found that an acute bout of static stretching resulted in decrements in subsequent force and power development. Aguilar et al. (2012) compared the acute effects of a dynamic warm-up and static stretching warm-up on muscle flexibility, strength, and vertical jump using a randomized controlled trial design. The authors randomly assigned forty-five participants into a control, static stretching warm-up or a dynamic warm-up group. All participants performed a general warm-up for 5-minutes (on a stationary bicycle) and then completed a 10-minute warm-up protocol. During this protocol, the dynamic group performed dynamic stretching and running, the static group performed static stretching, and the control group rested. The authors found that in the dynamic warm-up group, there was a significant increase in hamstring flexibility and eccentric quadriceps peak torque. The control and static stretching groups did not significantly affect any flexibility, strength, or vertical jump measures.

Palmer et al. (2019) conducted a randomized, crossover repeated measures study design in thirteen young healthy female participants (21 years). The authors examined the acute effects of different static stretching durations (30-, 60-, and 120-seconds) of the hamstrings on maximal strength and the rate of force development, which is a construct of power. The researchers found significant declines in muscle power with 120-seconds of-static stretching. It was found that shorter durations of stretching (30 -and 60-seconds) had no effect. This supports previous findings that indicates a dose-response relationship between stretching duration and stretching-induced decrements in performance, where stretching duration under 60 - to 90-seconds have no effect on performance. As stretching times increases beyond 120-seconds, several reports of impaired high-intensity performance have been published (Behm and Kieble, 2007; Behm and Chaouachi, 2011). This aligns with the ‘real world’ practice used by coaches and trainers to have athletes ‘loosen up’ with several short-duration stretches prior to specific warm-up tasks, leaving long-duration stretching, if required, to distinct sessions separated from workouts targeting the development of strength, speed and power.

Caldwell et al. (2019) investigated the acute effects of prolonged unilateral hamstrings static stretching (120 seconds) on maximum voluntary isometric contraction of the knee extensors and of the ipsilateral and contralateral legs during a drop jump assessment, testing both ground contact time and jump height in a cohort of 40 participants including trained and recreationally active males and females. Specifically, the static stretching involved four repetitions of 30-second. The authors found a significant performance decline in knee extensor strength after static stretching in both, the ipsilateral and contralateral leg. The researchers performed the static stretching in isolation and the performance tasks were assessed 60-seconds after the stretching. These findings support the both concepts of (1) a dose dependant response of stretching and performance and (2) that certain high-intensities activities are time-sensitive. That is, in ‘real world’ settings, the gap between finishing stretching and maximal performance is typically several minutes and not sixty seconds. The average time of performance testing in our study was approximately 120-seconds, which agree is Blazevich et al. (2018), who also observed no effect on performance when stretching was separated from testing by several minutes.

Pulverenti et al. (2019) examined the acute effects of intense, passive long duration static stretching of the plantar flexor muscles (5 × 60-seconds) on maximal voluntary isometric torque in fourteen healthy male participants. The authors reported a significant decrement in maximal voluntary plantar flexion torque after static stretching. The participants performed a total of 5-minutes of static stretching on the calf muscles and the stretching was performed in isolation and not as part of a comprehensive warm-up routine. These findings add to our knowledge that stretching durations longer than 120-seconds immediately prior to the performance of activities requiring maximal force production result in impaired ability.

In a recently published narrative review, Lima et al. (2019) concludes, positively, that the collective literature demonstrates that prolonged static and PNF stretching can improve flexibility. Negatively, however, without additional dynamic activities (i.e. full warm up) neuromuscular force and power outputs can be impairments. Lima et al. (2019) raises the salient point: laboratory investigations are commonly plagued with an artificial construct, that is, the acute effects of stretching *as a warm-up* rather than a real-world approach, which is stretching *as part of* a warm-up routine.

In a recent review, Chaabene et al (2019) also notes that this one of the primary issues that has confounded the external validity in the previous literature: stretching was mostly applied in the studies that reported negative acute performance changes as a single-mode intervention or in the form of an isolated component during a warm-up program. This is an artificially myopic and laboratory-based way of examining the effects of stretching on performance that does not reflect real-world praxis. In training practice, stretching is most often part of an integrated full dynamic warm-up program.

Blazevich et al. (2018) identified the identical issues that was reported in the present original thesis in the Justification Section (1.2). We agree that the limitations in methodology of the previous literature have included a) total stretching durations being longer than those typically performed by athletes and (b) the stretching rarely being followed by other important components of a sport-specific warm-up. These include high-intensity and movement pattern-specific exercises.

A further issue in the previous literature, also noted in the Justification, was recently proffered by Lima et al. (2018) that testing was often conducted immediately after the stretching intervention, whereas in the real world, a typical warm-up routine would have a period of time between the general warm-up (with stretching), the specific warm-up sets or activity rehearsal and the actual performance task or sport activity.

Accordingly, Blazevich et al. (2018) conducted their investigation to examine the effects of static and dynamic stretching routines performed as part of a comprehensive warm-up on flexibility and sprint running, jumping, and change of direction tests in team sport athletes. The investigators reported no effects of stretch condition on test performances. Furthermore, participants reported that they felt more likely to perform well when stretching was performed as part of the warm-up, irrespective of stretch type. However, no effect of muscle stretching was observed on flexibility and physical function compared with no stretching. The authors concluded that short durations of either static or dynamic stretching, when included as part of a comprehensive warm-up, is unlikely to affect sprint running, jumping, or change of direction performance. These findings underscore the importance of research utilizing 'real world' practice, which can be applied in sports and fitness performance settings.

Similarly, Samson et al. (2012) studied participants under four warm-up conditions including a 1) general aerobic warm-up with static stretching, 2) general aerobic warm-up with dynamic stretching, 3) general and specific warm-up with static stretching and 4) general and specific warm-up with dynamic stretching. The authors found no differences in rapid kicking, vertical jump, or 20-metre sprint test performances between static and dynamic stretch conditions when performed as part of a warm-up routine that had both general components (stretching and cardiovascular) and specific warm-up activities in this cohort of both recreational and competitive athletes. The findings of Samson et al. (2012) agree with other modern studies that have demonstrated the short-duration stretching, as part of a wider, comprehensive warm-up, do not impair high-intensity performance.

Reid et al. (2018) examined the effects of different stretching durations (i.e., 30, 60, or 120 seconds) of the knee flexors (hamstrings) and extensors (quadriceps) as part of a full warm-up practice (aerobic activity, dynamic stretching, sport-specific activities) on muscle strength and power (i.e., jump height) in sixteen physically active male participants. The investigators found that while all stretch durations improved ROM, clear reductions in strength and power measures were found with 120 seconds of static stretching per muscle group, even within a comprehensive warm-up. However, the authors found that moderate durations of static stretching (60-seconds) were observed to improve ROM whilst either having negligible or beneficial (but not detrimental) effects on specific aspects of athletic performance requiring strength and power (knee extension and flexion force and vertical jumping, respectively). This provides further support to the dose-dependent findings of previous literature, that is, stretching durations under 120-seconds do not appear to impair performance. Stretching periods approximately 120-seconds and longer may negatively impact high-intensity performance tasks. A unique finding of Reid et al. (2018) is that a full warm-up could not ameliorate the performance decrements induced by long duration stretching.

Bengtsson et al. (2018) studied whether sport-specific exercises could rescue the negative effects of longer duration static stretching over 60 seconds on peak torque of the knee extensors in fifteen active physical education male and female students. The researchers examined two different warm-ups: a 2-component warm-up and a 3-component warm-up. Both protocols contained low intensity aerobic exercise and sport-specific exercise, whereas the 3-component warm-up also contained static stretching. After the warm-ups, the subjects performed an isokinetic knee flexion and extension test. During the testing, muscle performance of peak torque, mean power, and total work was recorded. These authors reported no negative effects of static stretching on isokinetic muscle performance when followed by sport- specific exercises. These data support the findings of others (Blazevich et al. 2018) that stretching, when included as part of the comprehensive warm-up – as typically conducted in the 'real world' - do not impair performance.

Park et al. (2018) recently evaluated the effects of warm-ups with or without the inclusion of a stretching component in a nonathletic population of thirteen students. Subjects performed a non-warm-up, warm-up, or warm-up regimen with stretching prior to the assessment of the isokinetic moments of knee joints. The authors found no statistically significant intergroup differences in the flexor and extensor peak torques of the knee joints at 60°/sec, which were assessed to measure muscle strength. Further, no statistically significant intergroup differences were found in the flexor and extensor peak torques of the knee joints at 180°/sec, which were assessed to measure muscle power. Finally, the total work of the knee joints at 240°/sec, intended to measure muscle endurance, reported no statistically significant differences among the groups. The authors concluded that the addition of stretching during warm-ups had no effect on lower body strength, power and strength-endurance.

In a similar study design to Park et al. (2018), Sim et al. (2015) examined the influence of static stretching in a warm-up on the isokinetic muscle torque (at 60°/sec) and muscle power (at 180°/sec) of the flexor muscle and extensor muscle of the knee joint. The authors enrolled ten healthy students and performed short duration stretching protocols, consisting of two sets of stretching of 20-seconds each for the lower body muscles. They found that there was no statistical difference between short duration stretching compared with no stretching and concluded that a warm-up including two sets of stretching for 20 seconds per muscle group does not decrease muscle strength and muscle power.

Morrin and Redding (2013) also examined the effects of the addition of stretching types to a general warm-up on jumping ability, balance and ROM in a cohort of female trained dancers. The authors reported that static stretching, when performed as part of a full warm-up does not appear to be detrimental to a dancer's performance. It was found that dynamic stretching had some benefits but not in all three key area's tested, namely lower body power (VJ height), balance, and range of motion. However, combination stretching of both static and dynamic stretching showed significantly enhanced balance and vertical jump height scores and significantly improved pre-stretch and post-stretch ROM values. The authors concluded that a combined warm-up protocol consisting of static and dynamic stretching as part of a comprehensive warm-up should be promoted as an effective warm-up for dancers, where that performance requirements demand high amounts of flexibility.

Stretching in both sports and fitness settings commonly utilise the flexibility drills with the intention of ‘limbering up’ specific areas before specific warm-up sets, and not to maximise terminal range of motion. To this end, the studies by Park et al. (2018), Sim et al. (2015) and Morrin and Redding (2013) provide important observations about typical, short-duration stretching when included as part of a warm-up regime. These studies observed no performance effects. It could be argued that coaches and athletes have empirically known this to be the case for decades.

Another sport that requires high levels of flexibility is gymnastics. And similar to the study on dancers by Morrin and Redding (2013), comprehensive warm-ups have historically included various stretching methods to improve subsequent performance. Montalvo and Dorgo (2019) compared the effects of different stretching protocols on vertical jump measures. The authors studied male and female gymnasts in a randomized crossover study. Participants were measured on the countermovement jump, squat jump, and depth jump at baseline and were then randomly placed into one of four stretching protocols: Static, dynamic, static and dynamic, and dynamic and static stretching. The authors found that the dynamic protocol showed significant improvements in counter movement jump. The other interventions did not show any significant improvements. Thus, the investigators concluded that a warm-up consisting of dynamic movements that resemble those used in the sport of gymnastics can improve vertical jump measures. This agrees with previous findings that specific warm-ups should include movement patterns and demands that closely resemble the performance tasks and the addition of stretching, when part of the comprehensive general and specific warm-up, have no negative effect on subsequent performance.

Two similar studies were published in 2011 examining the effects of stretching within a comprehensive warm-up on power-based tasks. Perrier et al. (2011) examined the effects of a warm-up with static vs. dynamic stretching on countermovement jump height, reaction time, and low-back and hamstring flexibility They found that the countermovement jump height was greater for when a dynamic stretches were included in the warm-up compared to static stretching or no stretching, but static stretching did not impair performance. In a large study of one hundred male athletes, Kirmizigil et al. (2011) evaluated the effects of three different flexibility techniques: (a) ballistic stretching, (b) proprioceptive neuromuscular facilitation stretching with ballistic stretching, and (c) PNF + static stretching on vertical jump performance. The authors found that all warm-up types improved jumping performance when included as part of a comprehensive warm-up.

An example of research that examined the effects of a general warm-up (static stretching) with a specific warm-up (squatting) on power recorded during jump squats was reported by Buttifant and Hrysomallis (2015). The authors compared the acute effect of box squats with barbell, box squats with elastic resistance bands and static stretches on external power during a 20-kg weighted jump squat. Athletes performed each of the 3 warm-up protocols on separate occasions in a randomized order. Specifically, the barbell squat protocol involved 3 sets of 3RM, the banded squats involved 3 sets of 3 repetitions using highest resistance elastic bands, and the static stretching protocol involved two 30-second stretches for muscles of the lower limbs. The authors found that both squat warm-ups significantly improved jump power. However, the authors reported that power output significantly decreased when the static stretching protocol was performed prior to the jumping task.

The study of Buttifant and Hrysomallis (2015) is a typical example reported in the literature of a study design comparing a well-accepted method of warming-up prior to power development – that is, specific warm-up sets with high-intensity external load – with a modality designed to improve range of motion. However, it appears that there is little, if any preparation of the muscular apparatus to the specific demands of jumping (static stretching). The authors reported improved power development with the use of a warm-ups involving squats and decreased performance when static stretching was used in isolation. However, with the research design, it may be considered that this outcome was inevitable.

van Gelder and Bartz (2011) examined the effect of static and dynamic stretching on agility performance in male collegiate and recreational basketball athletes. This is the only study to address the effects of stretching on indices of agility performance in the last decade. The researchers randomly assigned participants to 1 of 3 intervention groups: static stretching, dynamic stretching, or no stretching. The authors found that dynamic stretching improved performance on closed agility skills involving a 180° change of direction and the static stretching or no stretching conditions had no impact on agility performance.

These studies support the findings of Taylor et al. (2009) along with Little and Williams (2006) that was previously reviewed. Briefly, Taylor et al. (2009) found no differences in vertical jump or 20-metre sprint performances after a progressive, skill-based warm-up in high-level netball athletes despite performance decrements being observed immediately after a preceding static stretch period. In a study examining professional English Premier League soccer players, Little and Williams (2006) reported no differences in 20-metre sprint time or vertical jump height after static or dynamic stretching when the stretching was performed as part of a full warm-up session.

The previous studies that report the use of stretching included in a wider, comprehensive warm-up are in alignment with real world practice, that is, stretching as part of a warm-up routine and not as a warm-up. These studies report that when stretching is part of the comprehensive warm-up, short duration muscle elongation does not compromise high-intensity exercise performance tasks. Superficially, this appears to contradict the consensus findings of previous research. However, when the literature is stratified into studies that provide a well-rounded warm-up routine, with both general and specific components, and studies that investigate only isolated stretching followed immediately by the performance tests, we see clear agreement that muscle stretching has no negative on high-intensity indices of muscle performance activities when comprehensive warm-ups are performed.

Finally, consideration to the effects of stretching of activities that specifically require stretch-shortening cycles must be given. Recently, Kallerud and Gleeson (2013), after reviewing 43 studies, reported that approximately half of the studies assessing the acute effect of static stretching reported a detrimental effect on performance, while the remainder found no effect. In contrast, dynamic stretching showed no negative effects and improved performance in half of the trials. The effect size associated with static and dynamic stretching interventions was commonly low to moderate, indicating that the effect on performance might be limited in practice. The authors concluded that ‘the recommended volume of static stretching required to increase flexibility might induce a negative acute effect on performances involving rapid SSCs, but the effect sizes of these decrements are commonly low, indicating that the acute effect on performance might be limited in practice. No negative acute effects of dynamic stretching were reported’. This is consistent with the perspective that stretching dose must always be considered and that the commonly used short duration stretching used as part of a full warm-up will not impair performance.

CONCLUSION FROM THE CURRENT LITERATURE

The literature on pre-exercise stretching has been the subject of controversy, confusion and debate over the past two decades. The general belief that pervades both academic and performance settings is that stretching impairs athletic ability and should be avoided in the warm-up period. As a consequence, it has been recommended to discontinue pre-exercise stretching in the warm-up routine, especially if strength, speed and power activities are to be subsequently performed

However, the period of 2011 to 2020 has seen substantial evidence supporting the position that pre-exercise stretching has no effect or, at worst, has only a trivial negative impact on subsequent activities requiring strength, speed- and power development. Furthermore, the literature has refined the topic by providing the context of this recommendation: the accumulated duration per muscle group should not exceed 60 seconds and specific warm-up sets or performance dress rehearsals should be undertaken to minimize any potential negative influence of stretching on the specific activity.

Another initial assumption based on the previous literature that has been recently addressed is the time-course between stretching and the specific performance activities. Numerous studies cautioned against the use of all stretching before muscular performance. This was based on studies that that reported performance tests conducted immediately after stretching. However, the modern studies have shown that short intervention-test periods are not typical in the performance settings and when evaluated within a comprehensive warm-up routine, performance changes were typically statistically trivial unless extreme stretch protocols were used (Fowles et al. 2000; Power et al. 2004).

In sum, the negative acute effects of stretching must be interpreted from the perspectives of (1) dose-response and (2) as part of a comprehensive warm-up routine. Modern studies have established that stretching conducted over short durations of 60-seconds per muscle group or less can be recommended without fear of negative effects on performance. In support of this perspective, Kay and Blazevich (2012) state 'shorter durations of stretch (<60-seconds) can be performed in a preexercise routine without compromising maximal muscle performance'. However, the data suggests that long- duration (2-minutes and longer per muscle group) stretching may have negative effects on strength, speed and power performances (Kay and Blazevich, 2012; Behm et al., 2016; Caldwell et al., 2019; Palmer et al., 2019; Pulverenti et al., 2019).

These findings are at odds the widespread and commonly held opinion in both sports settings and fitness industry that pre-exercise stretching worsens muscular performance in activities requiring strength, speed and power development. Recent studies demonstrate that it is primarily a matter of total stretching duration and the use of specific warm-up routines between stretching and performance (Reid et al., 2018; Blazevich, et al., 2018; Taylor et al. 2009; Murphy et al. 2010). Specifically, modern studies incorporating a detailed and comprehensive warm-up (i.e. aerobic activity, stretching, and dynamic sport specific activity, such as warm-up sets) have not shown any performance decrements with a typical stretching duration used in the 'real world' (Blazevich et al., 2018). There is data to suggest, however, that more excessive stretching durations of over 2 minutes per muscle group might negatively impact performance (Reid et al. 2018), and therefore, should be cautioned against using in the warm-up period.

The original impetus for undertaking this research project in the early 2000's was to assess and compare what 'we' (as a strength coach in sports and fitness development) did routinely in our warm-ups with what authors of laboratory-based investigations were beginning to tell us we 'should' be doing. I felt this was at odds with and not at all representative with what was done in the 'real world' and I sought to design a study that reflected 'real world' practice, in attempt to help solve this false dichotomy that existed between coaches and academics.

Our findings indicated that, on the whole, when stretching was performed for realistic durations (around 60-seconds) or included as part of a wider warm-up (with specific warm-up sets), contrary to opinion at the time, no performance impairments were observed. The application of these findings to sports and fitness settings is twofold: (1) if one feels the need to loosen up for around a minute per muscle group before activities that require strength speed or power, feel free to include various stretches prior to your specific tasks without fear of reducing work output. And (2) there is no difference in performance if short-duration stretches are included in the warm-up or if specific warm-up sets alone are used prior to high-intensity activities.

Individuals exercise or train daily for health, performance and aesthetics, so these findings are directly relevant to a huge number of persons who have ever asked 'how should I best warm-up?' Contrary to studies that used an artificial, laboratory-based approach to answer this question, our results suggest (a) stretch if you feel you would receive benefit from doing so, with the proviso of limiting the stretching to around a minute per muscle group and (b) perform warm-up sets of the specific task you are about to undertake. When an industry-informed approach is taken to limit stretch duration dose or to include a broader, comprehensive warm-up, the last decade has witnessed agreement with several studies reporting identical findings to our own and to what many coaches and trainers have empirically discovered through the experience of coaching.

The last two decades has witnessed a shift in research methodology that commenced in the early 2000's with an academic approach and progressed in time to a more realistic, practical examination of the research questions. Specifically, original investigations sought to discover the impact of maximal tolerable and extended duration stretching on muscular properties, such as dynamic performance. More recent studies utilized shorter duration stretching, often as part of a comprehensive warm-up. Our original study was the first to identified that the literature of that time did not reflect real world practice but yet was being used as the basis for recommendations of industry bodies to guide practice. Thus, the study served as a platform for future investigations to extend our findings. A number of recent reports have validated our original methodological approach and results, that, as part of a comprehensive warm-up or in small doses, stretching does not negatively impact performance and should therefore not be feared in a warm-up routine.

DIRECTIONS FOR FUTURE RESEARCH

There are a number of suggestions that can be made to improve study design and application of the scientific findings to the fitness and athletic populations. Firstly, many stretch prior to exercise and training because they are either sore and stiff from the previous day's activities or from sitting for prolonged periods. These individuals stretch because it makes them feel like they move and perform better and more comfortably. Therefore, investigations can be conducted to assess subject's perceived comfort and ability to move and perform with and without prior stretching.

Secondly, many individuals undertake exercise with flexibility asymmetries. Using movement positional sensors before and after stretching treatment can easily identify if stretching can improve joint movement aberrations, which may have a potential to minimize overuse injuries in time.

Thirdly, again using positional sensors, pre-exercise stretching can be used to assess strength training exercises that require marked range of motion, such as squats, deadlifts and overhead movements. Can stretching be used as a quick and efficient means to bring about augmentation in movement ROM?

Fourthly, using ROM assessments to determine which candidates are most likely to receive the most benefits from pre-exercise stretching. Put another way, if an individual already processes a marked degree of flexibility, does that individual benefit from further stretching? Or is it limited to those who have limited joint ROM? Further studies are required to establish this.

Fifthly, the majority of studies have evaluated the effects of acute stretching on performance. What remains to be well studied is the chronic stretching load and frequency on muscular performance.

Finally, given the widespread belief that pre-exercise stretching will impair subsequent performance, and the fact that the majority of studies in this area have been conducted on subjects who are often exercise science students, who have read the literature and thus have an expectation of stretch-induced impairments. Future research should be performed on a cohort with no prior knowledge of this topic to minimize the effect of prior belief on outcomes.

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REFERENCES

Aguilar, A. J., DiStefano, L. J., Brown, C. N., Herman, D. C., Guskiewicz, K. M. & Padua, D., A. *Journal of Strength Conditioning Research*. (2012). A Dynamic Warm-Up Model Increases Quadriceps Strength and Hamstring Flexibility, 26(4):1130-41.

Behm, D. G., Blazevich, A. J., Kay, A. D. & McHugh, M. (2016). Acute effects of muscle stretching on physical performance, range of motion, and injury incidence in healthy active individuals: a systematic review. *Applied Physiology in Nutrition & Metabolism.* 41: 1–11.

Bengtsson, V., Yu, J.-G. & Gilenstam, K. (2018). Could the negative effects of static stretching in warm-up be balanced out by sport-specific exercise? *Journal of Sports Medicine &. Physical Fitness* 58: 1185–1189.

Blazevich, A. J., N. D. Gill, T. Kvorning, A. D. Kay, A. G. Goh, B. Hilton, E. J. Drinkwater, & D. G. Behm. (2018). No Effect of Muscle Stretching within a Full, Dynamic Warm-up on Athletic Performance. *Medicine & Science in Sport and Exercise*, 50(6): 1258–1266.

Buttifant D, Hrysomallis C.J (2015). Effect of Various Practical Warm-Up Protocols on Acute Lower-Body Power. *Strength & Conditioning Research,* 9(3):656-60.

Caldwell, S. L., Bilodeau, R. L. S., Cox, M. J., Peddle, D., Cavanaugh, T. & Young, J. D. (2019). Unilateral hamstrings static stretching can impair the affected and contralateral knee extension force but improve unilateral drop jump height. *European Journal of Applied Physiology,* 119:1943–1949.

Chaabene, H., Behm, D. G., Negra, Y. & Granacher, U. (2019) Acute Effects of Static Stretching on Muscle Strength and Power: An Attempt to Clarify Previous Caveats. *Frontiers in. Physiology, 10:1468.*

Kallerud, H. & Gleeson, N. (2013). Effects of stretching on performances involving stretch-shortening cycles. *Sports Medicine.* 43:733–750.

Kay, A. D. & Blazevich, A. J. (2012). Effect of acute static stretch on maximal muscle performance: a systematic review. *Medicine & Science in Sport and Exercise,* 44:154–164.

Kay, A. D., Husbands-Beasley, J. & Blazevich, A. J. (2015). Effects of contract– relax, static stretching, and isometric contractions on muscle–tendon mechanics. *Medicine & Science in Sport and Exercise,* 47:2181–2190.

Kirmizigil, B., Ozcaldiran, B., Colakoglu, M. (2014). Effects of Three Different Stretching Techniques on Vertical Jumping Performance. *Journal of Strength & Conditioning Research,* 28(5):1263-71.

Konrad, A., Reiner, M. M., Thaller, S. & Tilp, M. (2019). The time course of muscle-tendon properties and function responses of a five-minute static stretching exercise. *European Journal of Sports Science,* 19: 1195–1203.

Lima, C. D., Ruas, C. V., Behm, D. G. & Brown, L. E. (2019). Acute effects of stretching on flexibility and performance: a narrative review. *Journal of Science in Sports & Exercise,* 1:29–37.

Matsuo, S., Suzuki, S., Iwata, M., Banno, Y., Asai, Y. & Tsuchida, W. (2013). Acute effects of different stretching durations on passive torque, mobility, and isometric muscle force. *Journal of Strength & Conditioning Research, 27*:3367–3376.

Montalvo, S., Dorgo, S. (2019). The Effect of Different Stretching Protocols on Vertical Jump Measures in College Age Gymnasts. *Journal of Sports Medicine & Physical Fitness,* 59(12):1956-1962.

Morrin, N., Redding, E. (2013). Acute Effects of Warm-Up Stretch Protocols on Balance, Vertical Jump Height, and Range of Motion in Dancers. *Journal of Dance in Medicine & Science,* 17(1):34-40.

Opplert, J. & Babault, N. (2018). Acute effects of dynamic stretching on muscle flexibility and performance: an analysis of the current literature. *Sports Medicine,* 48:299–325.

Palmer, T. B., Pineda, J. G., Cruz, M. R. & Agu-Udemba, C. C. (2019). Duration-dependent effects of passive static stretching on musculotendinous stiffness and maximal and rapid torque and surface electromyography characteristics of the hamstrings. *Journal of Strength & Conditioning Research,* 33:717–726.

Park, H. K, Jung, M. K., Park, E., Lee, C. Y., Jee, Y. S., Eun, D., Cha, J. Y., Yoo, J. J. (2018). The Effect of Warm-Ups with Stretching on the Isokinetic Moments of Collegiate. *Exercise in Rehabilitation*, 26;14(1):78-82.

Pearce, A. J., Latella, C., Kidgell, D. J. (2012). Secondary warm-up following stretching on vertical jumping, change of direction, and straight-line speed. *European Journal of Sports Science,* 12(2):103–12.

Pearce, A. J., Rowe, G. S. & Whyte, D. G. (2012). Neural conduction and excitability following a simple warm up. *Journal of Science in Medicine & Sport* 15:164–168.

Peck, E., Chomko, G., Gaz, D. V. & Farrell, A. M. (2014). The effects of stretching on performance. *Current Sports Medicine Research,* 13:179–185.

Perrier, E. T., Pavol, M. J., Hoffman, M. A. (2011). The Acute Effects of a Warm-Up Including Static or Dynamic Stretching on Countermovement Jump Height, Reaction Time, and Flexibility. *Journal of Strength & Conditioning Research,* 25(7):1925-31.

Pulverenti, T. S., Trajano, G. S., Kirk, B. J. C. & Blazevich, A. J. (2019). The loss of muscle force production after muscle stretching is not accompanied by altered corticospinal excitability. *European Journal of Applied Physiology,* 119: 2287–2299.

Reid, J. C., Greene, R., Young, J. D., Hodgson, D. D., Blazevich, A. J. & Behm, D. G. (2018). The effects of different durations of static stretching within a comprehensive warm-up on voluntary and evoked contractile properties. *European Journal of Applied Physiology* 118:1427–1445.

Samson, M., Button, D. C., Chaouachi, A. & Behm, D. G. (2012). Effects of dynamic and static stretching within general and activity specific warm-up protocols. *Journal of Sports Science & Medicine*, 11(2):279–85.

Sim, Y. J, Byun, Y.H, Yoo, J.J (2015). Comparison of Isokinetic Muscle Strength and Muscle Power by Types of Warm-Up. *Physical Therapy in Science,* 27(5).

Simic, L., Sarabon, N. & Markovic, G. (2013). Does pre-exercise static stretching inhibit maximal muscular performance? A meta-analytical review. *Scandinavian Journal of Medicine & Science in Sports,* 23:131–148.

Stone, M., Ramsey, M. W., Kinser, A. M., O'Bryant, H. S., Ayers, C. & Sands, W.A. (2006). Stretching: Acute and Chronic? The Potential Consequences**.** *Strength and Conditioning Journ*al, 12: 66-74.

Van Gelder, L. H., Bartz, S. D. (2011). The Effect of Acute Stretching on Agility Performance. *Journal of Strength & Conditioning Research,* 25(11):3014-21.