No effect of muscle stretching within a full, dynamic warm-up on athletic performance

Short title: Stretching during sports warm-up

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ABSTRACT

Purpose: 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.

Methods: A randomized, controlled, cross-over study design with experimenter blinding was conducted. On separate days, 20 male team sport athletes completed a comprehensive warm-up routine. After a low-intensity warm-up a 5-s static stretch (5S), 30-s static stretch (30S; 3×10-s stretches), 5-repetition (per muscle group) dynamic stretch (DYN) or no stretch (NS) protocol was completed; stretches were done on 7 lower body and 2 upper body regions. This was followed by test-specific practice progressing to maximum intensity. A comprehensive test battery assessing intervention effect expectations as well as flexibility, vertical jump, sprint running and change of direction outcomes was then completed in a random order.

RESULTS: There were no effects of stretch condition on test performances. Before the study, 18/20 participants nominated DYN as the most likely to improve performance and 15/20 nominated NS as least likely. Immediately before testing, NS was rated less ‘effective’ (4.0±2.2 on 10-point scale) than 5S, 30S and DYN (5.3-6.4). Nonetheless, these ratings were not related to test performances.

CONCLUSION: Participants felt they were 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 to no stretching. Based on the current evidence, the inclusion of short durations of either static or dynamic stretching is unlikely to affect sprint running, jumping or change of direction performance when performed as part of a comprehensive physical preparation routine.

Key words: athletic preparation, sprint performance, vertical jump, change of direction, muscle power, stretch-induced force loss.

INTRODUCTION

It is believed that the completion of a pre-exercise (or pre-sport) physical preparation routine is required to augment performance and reduce injury risk (1-3). One component of this routine that has received much scrutiny is the inclusion of static (particularly passive) muscle stretching (3-8). From an injury minimization perspective, studies have typically not confirmed a clear effect of pre-exercise static stretching on all-cause injury risk in sports (9, 10), which has resulted in some researchers suggesting a limited role for the practice (6, 7, 10) or for the inclusion of dynamic forms of stretching (2). However, other authors conclude that static stretching might specifically provide a small-to-moderate protective effect for muscle-tendon injury risk, especially in running-based sports (e.g. the various football codes and court sports) (3, 4, 8, 9), which attract by far the highest participation (11) and injury (12) rates. By contrast, no detailed studies have examined the effects of dynamic stretching on injury risk. Therefore, current scientific evidence favors static over dynamic stretching from an injury prevention perspective, even though the overall benefit may be small-to-moderate and limited to a subset of sports.

Nonetheless, several recent reviews have also concluded that static stretching can significantly and negatively impact high-intensity physical performance (4, 5, 13). Several researchers and advocacy groups, including the European College of Sports Sciences (14) and American College of Sports Medicine (15), do not recommend the inclusion of static stretching in pre-exercise routines, or call for its replacement by dynamic forms of muscle stretching (2). Indeed, in some cases the continued use of static stretching by sports participants has been explicitly admonished (16). Nonetheless, the majority of studies examining the effects of pre-exercise muscle stretching have not been designed to assess its effects on sports performance (e.g. see Supplement G in ref. 4). Common threats to external validity in previous studies include (a) total stretching durations being longer than those typically performed by athletes (17, 18), (b) the stretching rarely being followed by other important components of a sport-specific warm-up, including high-intensity and movement pattern-specific exercises (1, 19), even though it may mitigate the negative effects of stretching (20), (c) participants being only minimally familiarized with the tests (athletes, on the other hand, are familiar with their sporting skills), (d) differences existing in the execution (movement pattern) of static versus dynamic stretches, and (e) the imposition of non-stretching rest periods in control conditions/groups, which would not be performed in sports (4). Also, studies have been susceptible to serious threats to internal validity, such as the expectancy effects of knowledgeable participants (21) and lack of experimenter blinding (22). Notwithstanding these threats to validity, the effects of static stretching on dynamic movement performance (e.g. jumping, running, sprint cycling) have been found to be small on average when stretches are performed for <60 s per muscle (weighted average = -1.1%), and the performance benefits of dynamic stretching performance is also surprisingly small (+1.3%)(4). The call for the removal of static stretching and possible replacement with dynamic stretching (16), despite the limited evidence of impact on sports performance, creates a dilemma for medical practitioners, physiotherapists and physical trainers who may be asked to provide their opinions on proper sports participation practices.

Given the above, the decision to advocate against the static stretching, particularly on the grounds that it might reduce exercise performance, is questionable, especially given that sports participants show a preference to stretch their muscles despite this advocacy (23) and there being a potential small-to-moderate musculotendinous injury risk minimization benefit. In the present study, we have attempted to overcome some of the limitations of previous studies to specifically answer the question of whether the inclusion of short- or moderate-duration static or dynamic muscle stretching completed as part of a comprehensive pre-exercise routine (i.e. warm-up) influences performances in common, high-intensity sporting tasks. Based on the available evidence, we hypothesized that the imposition of short or moderate durations of static or dynamic stretching would not meaningfully impact high-intensity physical performance when performed as part of a comprehensive pre-exercise routine.

METHODS

Twenty healthy males (age = 21.1 ± 3.1 years; body mass = 73.4 ± 6.8 kg; height = 1.79 ± 0.70 m) volunteered for the study. Participants were recruited if they were: 18 - 25 years of age; without recent injury or illness that would preclude exercise performance; and competing in running-based sports or performing at least three running-based exercise sessions per week. The study was approved by the Human Research Ethics Committee of Edith Cowan University (STREAM11450/11541) and conducted in accordance with the Declaration of Helsinki. All participants read and signed an informed consent document.

Study design

This study used a randomized, cross-over (repeated measures) design with control condition, and was designed to assess the effect of dynamic vs. both shorter- (5 s) and longer- (30 s) duration static muscle stretching interventions on performances in tests that mimic common sporting tasks. There were three experimental (stretching) conditions and a non-stretching control condition (hereafter referred to as ‘pre-testing routines’) performed at the same time of day over four testing sessions separated by a minimum of 72 h and each followed by a comprehensive test battery (see Figure 1). The order of conditions and order of tests within each condition were randomized between the participants without replication by the participants choosing a numbered card randomly from a pack that related to a test and stretch condition order. The card was not replaced in order to ensure that some test and stretch condition orders could not be allocated more often than others.

A pre-testing routine was completed before the test battery was administered. The pre-testing routine, including any muscle stretching, was monitored by a research coordinator who ensured that procedures (described below) were followed correctly but who could not communicate with researchers overseeing the test battery (hereafter referred to as 'testers'). After completion of the pre-testing routine, the coordinators relinquished participant responsibility to the testers, who were given no information as to the pre-testing stretch condition administered and were naïve to the time required to complete the pre-testing routine; this prevented the possibility of guessing the pre-testing routine type since each required a different time to complete. Thus, the testers were blinded to the pre-testing routine condition.

Familiarization of muscle stretching and performance tests

At least one familiarization session was completed by each participant prior to data collection to become accustomed with the stretching protocols, learn the correct testing procedures, and acquaint themselves with the equipment, laboratory facility and the verbal instructions issued by the coordinators and testers for the stretching exercises and tests. A video demonstration of each stretch was provided to the participants in order to ensure similarity in instruction of the stretches, then each participant received individual feedback to correct errors. The participants were then shown how to complete each test and given multiple untimed trials to become familiar. The movement patterns of the tests (described below) were similar to the movement patterns used by the participants in their sports. An additional familiarization session was provided to four participants who declared a lack of confidence in the performance of one or more testing protocols.

Pre-study Participant Outcome Expectations

At the end of the familiarization session, each participant completed an outcome expectation survey to determine which pre-exercise routine they believed would prove most beneficial to performance. The participants were asked to "List in descending order the stretch condition you believe will stimulate the best improvement in your performance (dynamic, 5 s static, 30 s static and no stretch)" when compared to the other conditions. They therefore nominated in order from 1 to 4 (best to worst) which routine they believed would improve (or reduce) performance the most. Post hoc, these expectations were compared to the outcomes of the testing to determine whether expectation was aligned with outcome.

Testing Session Design

Participants were required to wear the same sports shoes and athletic clothing at each session, refrain from intensive exercise in the 24-h period before testing, and abstain from caffeine or any form of stimulant/depressant 24 h prior to testing. As the participants were team sport athletes, other physical training completed by the participants outside of the study was monitored (for type, volume and intensity) by the participants providing a log book record of their activities in the 48 h prior to testing as well as a rating of their muscle soreness from 1 to 10 to ensure that significant (>2 units) changes in their performance of, or recovery from, their programs did not occur. If the standard training programs of the participants were not adhered to, the testing session was to be cancelled and completed at least 72 h later, however no instances of this occurred.

Each session commenced with a short pre-stretching warm-up consisting of a 3-min jog at 50% of perceived maximum exertion, then 5-s high knees (to ~90° hip angle) and 5-s heel-to-butt (i.e. knee flexion) drills at 50% of maximum perceived exertion. Heart rate was obtained immediately after the warm-up phase by manual palpation of the carotid artery for post-hoc examination of the repeatability of efforts, i.e. repeatability of the physical intensities used (heart rate itself could not be used as a target for intensity because of its slow temporal response after exercise commencement).

Participants then completed one of three experimental (stretching) conditions or progressed immediately to the test-specific (i.e. ‘sport-specific’) warm-up (described below); note that a rest condition of equal duration to the experimental conditions was not included in the no-stretch (control) session as this is not typical sports practice. The four conditions were a 5-s of static stretching (5S), 30 s of static stretching (30S; 3 × 10-s stretches), a 5-repetition (per muscle group) dynamic stretch (DYN), and a no-stretch condition (NS) (see Text, Supplemental Digital Content 1, detailing the instructions [with photo] for each stretch). The 5S, 30S and DYN stretching protocols each consisted of nine stretches that were close replicates (in body position) of each other in order to minimize the effect of stretching movement pattern on test outcomes. The static stretches were held at the point of ‘discomfort’, and maximal ROM was achieved in the dynamic stretches by ensuring a secondary pulling-motion with each repetition. The order of pre-exercise routines was randomized without replication between participants to minimize order effects.

Following the stretches (or after progressing immediately from the low-intensity warm-up in NS) a test-specific (i.e. ‘sport-specific’), higher intensity warm-up was completed. This started with a 2-min moderate-intensity jog at 60% of perceived effort, and 5-s high knees and 5-s heel-to-butt kick drills at 60% of perceived maximum effort. The participants then performed three circuits of the six performance tests, which were organized into three activity groups: 1) running vertical jump, 2) squat jump, countermovement jump and drop jump, 3) T agility test, and 4) 20-m sprint run, and the participants completed them in an order identical to that of the following testing session (see below). The intensity of each circuit increased from 60% to 80% and then 100% of perceived maximal exertion with a 30-s walk recovery between each activity set. This second part of the pre-testing routine took approximately 15 min to complete.

In order to address the study design limitation relating to the time between completion of the final stretch and the commencement of testing (4), a 7-min passive rest period was imposed between the completion of the pre-testing routine and the start of testing. This was done to more closely simulate game- or match-day situations where a short pre-competition briefing or an individual-specific sport preparation period is completed before match or competition commencement and allowed a better determination of the likely effect of the different pre-exercise routines on game- or match-day performance.

Participants were permitted to consume plain water ad libitum throughout the testing sessions, and all sessions were conducted in the biomechanics laboratory at Edith Cowan University under similar environmental conditions. The test battery was completed in a circuit at specified testing stations: 1) sit-and-reach flexibility test, 2) running vertical jump test, 3) squat (SJ), countermovement (CMJ) and drop jump (DJ; from 40-cm height) tests, 4) T agility test, 5) 20-m sprint running test. The order of tests was randomized between participants without replication and then repeated at each session; however, the sit-and-reach test was always completed first in order to determine the effect of the pre-testing routine on flexibility (maximum range of motion) without the potential influence of other tests. The performance of the sit-and-reach test was not expected to influence performances in subsequent tests because of the short-duration of the stretch procedure. For the testing, 4 min was allocated to each test station so that constant test timing was achieved regardless of the order of tests. An audio signal prompted the commencement of each test.

Post-warm-up Participant Outcome Expectations

To address issues around expectancy bias (21), during the 7-min rest period prior to testing in each session the participants also provided a rating score ranging from 1 to 10 for "how effective you believe the warm-up will be on your performance", where 1 = no effect/ possibly harmful to performance, 2 = very small improvement to performance, 5 = noticeable improvement in performance, and 10 = performance will improve dramatically. Obtaining this information immediately after completion of each pre-testing routine was expected to yield different results to the outcome expectation survey completed in the study familiarization session, and thus to allow a better analysis of whether participant expectancy might influence study results. Equal ratings between conditions were allowed.

Testing Procedures

Sit-and-reach flexibility

The sit-and-reach test was conducted using the Flex-Tester apparatus (Novel Products Inc., USA). A double-leg protocol was used as prescribed by the Canadian Society for Exercise Physiology (24). Each participant was instructed to sit bare-footed with knees in maximal extension and with both feet together and flat against the device. The participant then exhaled and stretched forward with palms overlapping and fingertips aligned, holding the furthest end point for 2 s. The score was recorded to the nearest 0.1 cm and repeated after a 30-s rest, with the greatest touch distance used for analysis.

3-m running vertical jump

A jump-and-reach system (Vertec, Swift Performance Equipment, Australia) was used for the running vertical jump to directly measure jump height based on the difference between reach height and the jump height obtained. Reach height was obtained before each test with the participant standing in a static position underneath the Vertec device and reaching as high as possible with the arm touching their ear but with shoulders remaining parallel to the floor. The fingers displaced vanes (each 1 cm apart) within touching distance, and the maximum reach height was obtained. For jump testing, each participant's take-off foot was pre-determined during the familiarization session, and a self-selected starting position was assumed 3 m from the device, which was kept consistent across all testing sessions. At their own volition, the participant executed a running, single-leg jump to displace the vanes with the opposite hand. The maximum jump-and-reach height was recorded as the number below the score reflected on the Vertec device, and the true jump height was then calculated as the difference between the maximum jump-and-reach height and the standing reach height. Each participant was given a maximum of five attempts; however the test was stopped when the participant failed to further improve jump scores on two successive attempts. A 30-s passive rest was imposed between each jump, and the best (i.e. final) true jump height score was used for analysis.

Squat (SJ), countermovement (CMJ) and drop (DJ) jump

A piezoelectric force platform (987B, Kistler Instrumente, Switzerland) was used to measure vertical jump height using the flight time method (height = $\frac{1}{2}$ g $(t/2)^2$, where g = 9.81 m·s^{-2} and t = time in air). The analog signal from the force platform was converted to a digital signal using Bioware software (Kistler Instrumente, Switzerland) sampling at 1000 Hz. Flight time was identified as the period between take-off and contact after flight and this was obtained in each jump via analysis of the force-time curve. A 15-s passive recovery was imposed between each jump, which allowed the tester to record vertical jump height and to reset the systems for recording of the next trial. Two attempts were allowed for each jump type, however a third trial was completed if jump heights varied >5%. The best score was used for analysis.

SJ trials were performed from a squatted position with heels in contact with the platform and with a self-selected knee angle (~75°). Each participant's hands were kept on their hips throughout the jump and a countermovement was not allowed. The participant was instructed to hold the squat position for at least 2 s before jumping. Visual observation of both jumping technique and the force-time trace was made to ensure that there was no countermovement in the jump. Trials were repeated if a countermovement could be visually observed by the tester. CMJ trials were performed from a vertical standing position with hands on hips and knees about shoulder-width apart. The participants then executed a two-footed vertical jump immediately following an eccentric countermovement to a self-selected depth (although the thighs could not be lower than parallel to the floor (19)). In the DJ, the participant stepped horizontally off a 40-cm box onto the force platform and then immediately jumped vertically. The instruction was given to "jump with minimal ground contact time upon landing" and then to jump as high as possible. The starting position on the top of the box was identical to the CMJ start position.

T agility test

For the T agility (change of direction) test, participants started at their own volition from a standing start 0.4 m behind a start line, sprinted forwards to touch the base of a cone located 10 m in front of them, shuffled 5 m to the left to touch a cone, shuffled 10 m to the right to touch a cone, shuffled 5 m left to touch the center cone once again, and then ran backwards past the start line. A dual-beam photocell timing gate (Swift Performance, Australia) positioned at the start line was triggered when the participant broke the light beam after the start and was stopped when the participant completed the course. Each athlete faced forwards at all times and could not cross their feet while shuffling. The participants were instructed to use a standing sprint start and were not allowed to build momentum by rocking back and forth at the start line. They performed the test twice with a 30-s passive rest between and the fastest time was used for analysis.

20-m sprint run

The 20-m sprint test was performed on an indoor synthetic 60-m sprint track. The participants used the same starting position as for the T agility test, and ran with maximum speed to a cone placed 1.5 m past a 20-m mark. This cone was included to prevent the participants from decelerating before crossing the 20-m mark. The tester counted down and then instructed the participants to sprint at their own volition, and timing gates placed at 0 and 20 m measured running time. Two attempts were given with a 30-s walk-back recovery between attempts, and the fastest time was used for analysis.

Statistical Analysis

Using IBM SPSS statistical software (version 22; IBM, New York), repeated measures multivariate analyses of variance (MANOVAs) were performed to compare test performances between conditions (5S, 30S, DYN, and NS), whilst a repeated measures ANOVA was used to compare the performances between conditions specifically for sit-and-reach scores. The alpha level was set at 0.05, and significant main or interaction effects were examined in further detail using ANOVA and univariate tests, as appropriate. Additionally, magnitude-based inference tests were performed and the precision of estimation was calculated. Qualitative descriptors of standardized effects used the criteria: trivial < 0.2, small 0.2-0.6, moderate 0.6-1.2, large >1.2. Effects where the 95% confidence limits substantially overlapped the thresholds for small positive and negative effects (i.e. exceeding 0.2 of the SD on both sides of zero) were defined as unclear. Clear small or larger effect sizes (i.e., those with > 75% likelihood of being > 0.20), as calculated using the spread sheet developed by Hopkins (25), were defined as definitive. Precision of estimates was indicated with 95%

confidence limits, which defined the range representing the uncertainty in the true value of the (unknown) population mean (26). To better assess the similarity (or lack) of performances between trials, both Pearson's (r) and intra-class (ICC) correlations were calculated; no corrections were required for outliers or non-uniformity of scatter. ICC values less < 0.5, 0.5 - 0.75, 0.75 - 0.9, and > 0.90 were considered indicative of poor, moderate, good, and excellent reliability, respectively. 90% confidence intervals were also computed for ICC values, but this is not possible for r values calculated from multiple repeated measurements. Finally, the Bland-Altman method for calculating correlation coefficients for repeated measurements (within subjects) was used to determine if higher participant expectation scores were correlated with better performances (27).

RESULTS

Participant Bias

When assessed during the familiarization session (i.e. before the commencement of the data collection period), 18 of the 20 participants nominated DYN as the most likely beneficial pre-testing routine (i.e. they ranked it 1st out of the four conditions) whilst two participants nominated 30S as the most likely beneficial. Additionally, 15 of the 20 participants nominated NS to be least likely beneficial (i.e. ranked it 4th out of the four conditions) whilst five participants nominated 30S. The commonest ranking order among the participants was DYN > 5S > 30S > NS. Thus, there was a clear *a priori* bias within the participant group.

When asked upon completion of each pre-testing routine to rate (on a scale of 1 – 10) how effective they believed the routine would be for their performance, NS was rated consistently worst (4.0 ± 2.2), and 5S (5.7 ± 1.9) and DYN (6.4 ± 1.6) were rated statistically higher ($p<0.05$) than NS; a tendency towards a greater rating for 30S (5.3 ± 2.3) did not reach statistical significance. No statistical differences were observed between the three stretching conditions and, using magnitude-based inference, it was found that all three stretch conditions were rated definitively (>75%) higher by participants than the no-stretch condition, with 97%, 87% and 100% likelihoods of 5S, 30S and DYN, respectively, being perceived of greater benefit than NS. Nonetheless, correlation coefficients computed for repeated measurements (within subjects) were small, ranging -0.16 – 0.21 and with explained variance (R^2) ranging 0.1 – 4.5%, indicating a lack of relationship between ratings of perceived benefit and performance outcomes.

Jumping, running, change of direction and flexibility

No statistical differences were detected between conditions for the 3-m running vertical jump, SJ, CMJ, or DJ tests (p = 0.471 for condition × time interaction; see Figure 2), indicating a lack of effect of pre-testing routine on performance, and no statistical difference was detected between sessions 1 – 4, indicating a lack of order effect (i.e. effect of session number irrespective of condition). All three stretch conditions were definitively (>75% likelihood) found to elicit trivial effects on running vertical jump (95%, 92% and 86% likelihood of trivial effect for 5S, 30S and DYN, respectively) and CMJ (97%, 89% and 95% likelihood of trivial effect) performances when compared to NS. The effects on SJ (44%, 65% and 74% likelihood of trivial effect) and DJ scores (72%, 38% and 50% likelihood of trivial effect) were less clear in SJ (56%, 32%, and 22% likelihood of higher jump in 5S, 30S and DYN, respectively) and DJ (7%, 62% and 50% likelihood of lower jump).

No statistical differences were detected between conditions for the 20-m sprint run (p = 0.354 for condition × time interaction) or T agility test (p = 0.996; see Figure 3), indicating a lack of effect of pre-testing routine on performances. Furthermore, no differences were detected between sessions 1 – 4, indicating a lack of order effect. All three stretch conditions were found to definitively (>75%) elicit trivial effects on 20-m sprint run time (88%, 86% and 91% likelihoods of trivial effect for 5S, 30S and DYN, respectively) and T agility time (84%, 93% and 75% likelihood of trivial effect) when compared to NS.

No statistical differences were detected for sit-and-reach scores ($p = 0.076$ for condition × time interaction) between 5S (27.1 ± 8.9 cm), 30S (27.8 ± 8.8 cm), DYN (28.4 ± 8.36 cm) and NS (28.9 ± 9.2 cm). A definitively trivial effect of condition was observed for DYN (98% likelihood of trivial effect) when compared to NS, but 45% and 31% likelihoods of trivial effects for 5S and 30S, with 55% and 68% likelihoods of lower sit-and-reach scores, were observed in these conditions when compared to NS.

Reliability Analysis

Both Pearson's (r) and intra-class (ICC [±90%CI]) correlation analyses completed on the test data revealed a high between-session repeatability of performances for SJ ($r = 0.87$; ICC = 0.84[0.73-0.92]), CMJ ($r = 0.90$; ICC = 0.92[0.83-0.95]), DJ ($r = 0.88$; ICC = 0.87[0.78-0.93]), 3-step jump ($r = 0.92$; ICC = 0.92[0.85-0.96]) and 20-m sprint running ($r = 0.93$; ICC = 0.92[0.87-0.96]) tests despite the different stretching interventions being imposed. Reliability estimates were slightly lower, but still moderate, for the T agility test ($r = 0.70$; ICC = 0.71[0.54-0.84]).

Pre-testing routine intensities

Heart rates measured immediately upon completion of the low-intensity jogging bouts during the pre-testing routine were not different between conditions. The heart rates after the 3-min jog at 50% of perceived maximum exertion (before the stretching) and after the 2-min jog at 60% of perceived exertion (after the stretching) were 125 ± 4 bpm and 139 ± 19 bpm, respectively.

DISCUSSION

The main finding of the present study was that the inclusion of a period of either static (passive) or dynamic stretching within a comprehensive pre-exercise physical preparation routine (i.e. a 'warm-up') did not detectibly influence flexibility or maximal vertical jump, sprint running acceleration or change of direction (T agility) test performances compared to a no-stretching control condition. In fact, inter-session test reliability coefficients were good to excellent for 3-m running, squat, countermovement and drop jump (ICC = 0.87 – 0.92) and 20-m sprint running (ICC = 0.93) tests, and moderate (ICC = 0.71) for the T agility test, despite the stretching component of the warm-up differing between sessions. Based on these results, athletic individuals who are well familiarized with the physical performance tasks and who complete a properly-structured warm-up period (e.g. ref. 1) may not experience alterations in performance when short- or moderate-duration muscle stretching interventions are included within the warm-up period. The participants showed a clear bias in their beliefs with regard to the effects of stretching in the warm-up routine, with 90% (18/20) of participants expecting performances to be better after inclusion of a dynamic stretching period when asked to "list in descending order the stretch condition you believe will stimulate the best improvement in your performance". This might result from participants having knowledge of sports science research, either as a university-level student or as an interested reader. It may also have influenced perceptions of preparedness for high-intensity physical activity after the warm-up period, with participants scoring 6.4 ± 1.6 on a 1 – 10 scale after a warm-up incorporating dynamic stretching when asked to rate "how effective you believe the warm-up will be on your performance" (1 = no effect/possibly harmful, 5 = noticeable improvement in performance, 10 = performance will improve dramatically). Nonetheless, no statistical difference was observed between ratings after any stretching condition, and warm-up routines incorporating 5-s static, 30-s static or dynamic stretching were 97%, 87% and

100% were likely to be perceived of greater benefit than when no stretching was allowed. Furthermore, correlation coefficients (computed for repeated measurements within subjects; (27)) were small (R^2 = 0.1 – 4.5%), indicating a lack of relationship. These data differ slightly from those presented recently by Janes et al. (21), where improvements in knee extensor, although not knee flexor, strength were observed after static stretching in participants who were told that the stretching should improve performance (i.e. there was an expectancy effect). We conclude that the participants felt as though the warm-up period prepared them better for high-intensity exercise performance when stretching was performed, irrespective of the type of stretching, than when no stretching was allowed. Whilst such beliefs did not meaningfully influence test performances in the present study, participants might theoretically perform better in a competitive sport environment when their perceptions of preparedness are higher, and this might be examined in future studies.

The current results, that static (passive) muscle stretching did not compromise, and dynamic stretching did not enhance, high-intensity exercise performance (Figures 2 and 3), appear to contradict the consensus findings of previous research. However, several previous studies have shown a lack of effect of muscle stretching on high-intensity exercise performance when comprehensive warm-ups were performed. Taylor et al. (20) found no differences in vertical jump and 20-m 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 (VJ = -4.2% and 20-m sprint = -1.4%). In professional (English Premier League) soccer players, Little and Williams (28) observed no differences in 20-m sprint time or CMJ height after static or dynamic stretching, although a statistically faster zig-zag agility (change of direction) performance after dynamic stretching, when the stretching was performed as part of a full warm-up session (notably, 20-m sprint performance was improved in both static and dynamic stretch conditions). Also, Samson et al. (19) found no differences in rapid kicking, CMJ or 20-m sprint test performances between static and dynamic stretch conditions when performed alongside general and specific warm-up activities in recreational and competitive athletes. Such outcomes are not always observed when a warm-up opportunity is provided, however. Static stretching has resulted in decrements in high-intensity exercise performances when the sport-specific warm-ups were brief (e.g. 2 × 50-m sprints (29)) or of moderate duration and/or intensity (e.g. 10-m high knees, side-stepping, carioca and skipping and 20-m zig-zag run; (30, 31)). When considered together, the available evidence indicates that muscle stretching does not influence high-intensity exercise test performances when they are followed by a warm-up period of sufficient duration and incorporating exercises performed at high (or maximal) intensities. Such warm-up periods have been endorsed for the improvement of sports performance and reduction in musculoskeletal injury risk, even when static stretching is incorporated (3, 32).

It is of practical importance that static or dynamic stretching early in the warm-up did not improve flexibility more than warm-up alone, as measured by a maximal sit-and-reach test. Time constraints did not allow for the specific testing of ranges of motion at different joints, however a single, multi-joint test was expected to reveal changes given that nine different stretches were performed. The lack of change in sit-and-reach distance indicated that any effect of a stretch condition within the warm-up on maximal range of motion was negligible, which is in agreement with previous evidence (33). Thus, the dynamic warm-up activities may have elicited improvements in maximal range of motion that were not improved upon by the performance of further stretching, as has been observed previously (34, 35). Alternatively, changes may have occurred in muscles other than those in the lower back and hamstrings and did not meaningfully impact sit-and-reach performance. While it cannot be excluded that the addition of muscle stretching to a warm-up routine might improve maximal range of motion at specific joints, especially if longer or more intense stretch periods are practiced (36), the present results indicate that stretching provided negligible flexibility benefit in addition to the low- and high-intensity dynamic activities (i.e. high knees, butt kicks and test practice) of the warm-up. It would be of interest to determine whether the stretching protocols evoked changes in muscle-tendon stiffness (extensibility) as opposed to maximum length (range of motion), as these have been shown to be differentially influenced by warm-up and stretching (36). Nonetheless, any possible effects in the current study were clearly insufficient to affect physical performance.

Steps were taken in the current study to improve both the external and internal validity of the results. With respect to external validity, we accepted only participants who competed in running-based sports or performed at least three running-based exercise sessions per week, and then allowed time for extensive familiarization of the tests. We also used stretching durations that are common in athlete populations (17, 18), ensured that the static and dynamic stretch movement patterns were identical, did not allow a passive rest condition in the non-stretch condition, and imposed a 7-min no-activity period after the completion of the full warm-up period. These steps were taken to replicate as closely as possible what might occur in the sporting environment. With respect to internal validity, we ensured that the researchers who conducted the tests were blinded to the warm-up conditions completed by the participants (although these were closely supervised by another researcher) and all instructions were scripted so that they were identical on each test occasion; the stretch maneuvers were also shown by video with written instructions so that variations in instruction were minimized. It was not possible to recruit participants who lacked prior knowledge of the potential effects of stretching. However, by assessing participant beliefs before the study as well as after the completion of each warm-up condition we were able to examine relationships between participant expectation and study outcomes. Together, these steps will have reduced both experimenter and participant bias, allowing us to more confidently accept the study outcomes. It should be acknowledged, however, that the study was not designed to examine the effects of prolonged periods of static (passive) stretching performed *immediately* prior to a physical task, as might be reflective of practice in some rehabilitation and resistance training settings.

One potential limitation of the current study design is that the tests were conducted in a circuit, with 4 min being allowed for the completion of each test block (i.e. 3-m running jump; SJ, CMJ, DJ; 20-m sprint run; T agility test). Therefore, the final test on any test day may have commenced up to 12 min after the commencement of the test battery, and it will have been performed after several other maximal-intensity tests. It can then be questioned whether tests performed closer to the end of the warm-up period might have been more strongly influenced by the interventions. However, our analysis did not reveal any evidence of an order effect of the tests so performances achieved when a test was first in the circuit (immediately after the 7-min imposed rest) were not different to those when the same test was completed at another time point. Based on this evidence, it appears that the (lack of) effect of the stretching is consistent when a full warm-up is completed and a short post-warm-up rest is imposed regardless of the time elapsed or the number of other tests performed in the intervening period.

CONCLUSIONS

The results of the present randomized, controlled, cross-over trial indicate that neither short- or moderate-duration static (passive) nor dynamic muscle stretching influence flexibility or high-intensity running, jumping or change of direction (agility) performances in young, athletic individuals who perform a complete, progressive pre-exercise warm-up routine. However, the incorporation of static (passive) or dynamic stretching into a warm-up routine allowed for individuals to feel more confident of high performance in the ensuing sports-related tests; i.e. there was a psychological effect. Based on the present results and previous findings of small-to-moderate reductions in muscle injury risk in running based sports, we conclude that short- or moderate-duration static stretching should be allowed, or even promoted, as part of the warm-up routine prior to sports participation. According to our results, dynamic stretching practices may also be incorporated into the warm-up routine, although it should be reminded that no data currently exist documenting the influence of dynamic stretching on injury risk.

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The results of the present study do not constitute endorsement by the American College of Sports Medicine. The authors declare that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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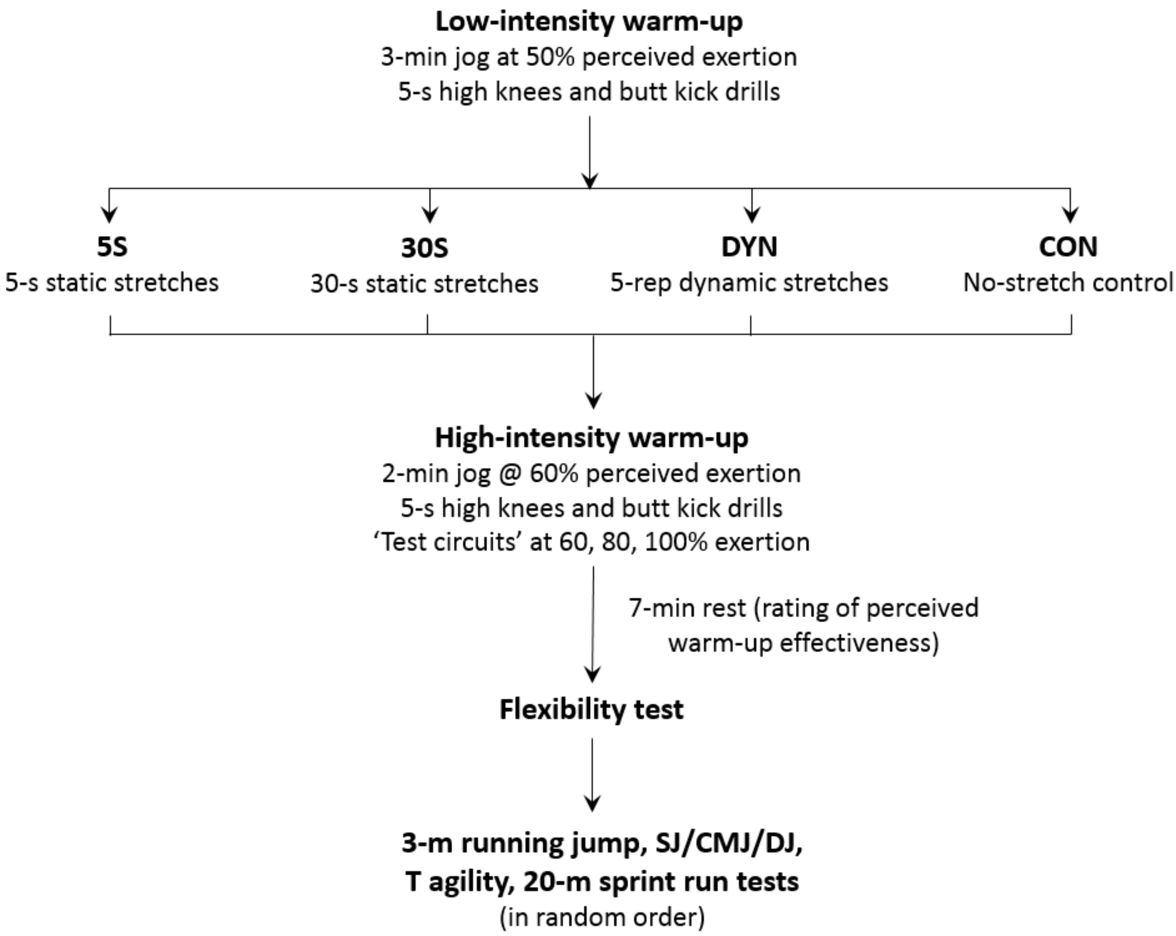

Figure 1. Study design. After completing a low-intensity warm-up including 3-min jog and running drills, a randomly-assigned stretching (no no-stretch control) condition was completed. This was followed by a high-intensity warm-up comprising further jogging and running drills and then three circuits at increasing intensity (to maximum) comprised of the performance tests. After a 7-min rest, during which time the participants rated their confidence that the warm-up would improve their performance (see text for details), a sit-and-reach flexibility test was completed before the high-intensity performance tests were completed in a random order (order repeated at each session). 5-rep: 5-repetition.

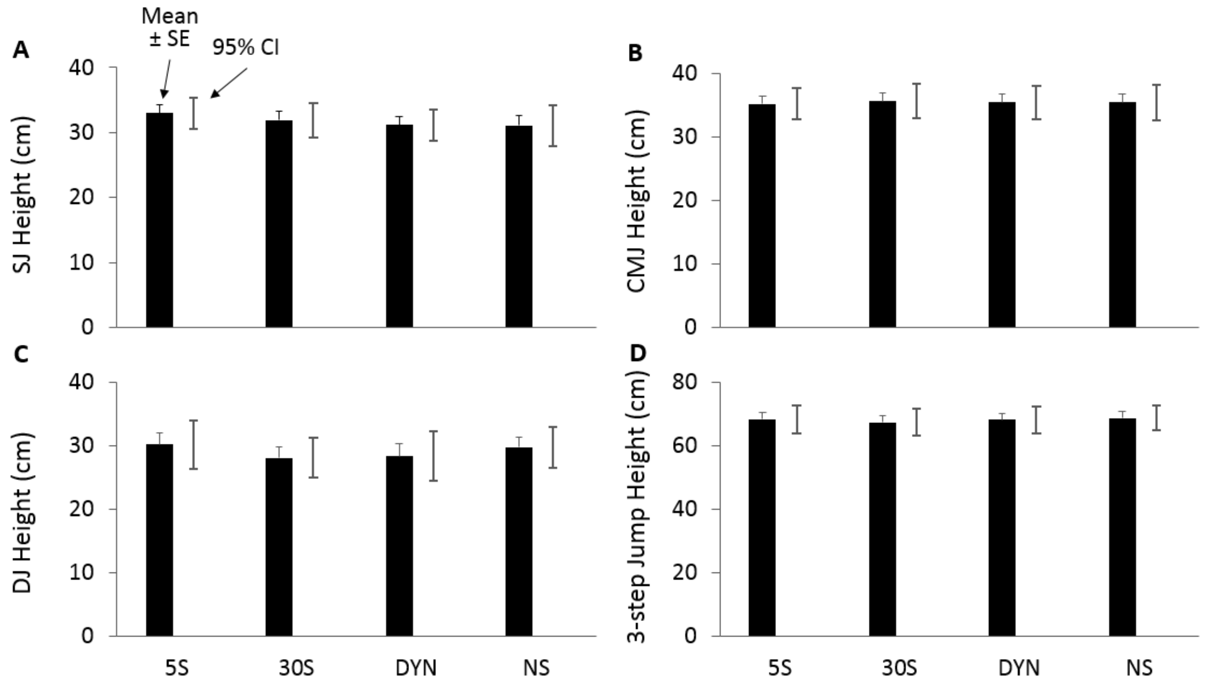

Figure 2. Squat (SJ; A), countermovement (CMJ; B), drop (DJ; C) and 3-step running (3-step Jump; D) heights recorded in 5S (5-s static stretch), 30S (30-s static stretch), DYN (dynamic stretch) and NS (no-stretch, control) conditions. There were no differences in jump test performances between the conditions. Shown are the mean ± SE (black column with error bar) and 95% confidence intervals of the mean (separate gray bar) jump performances.

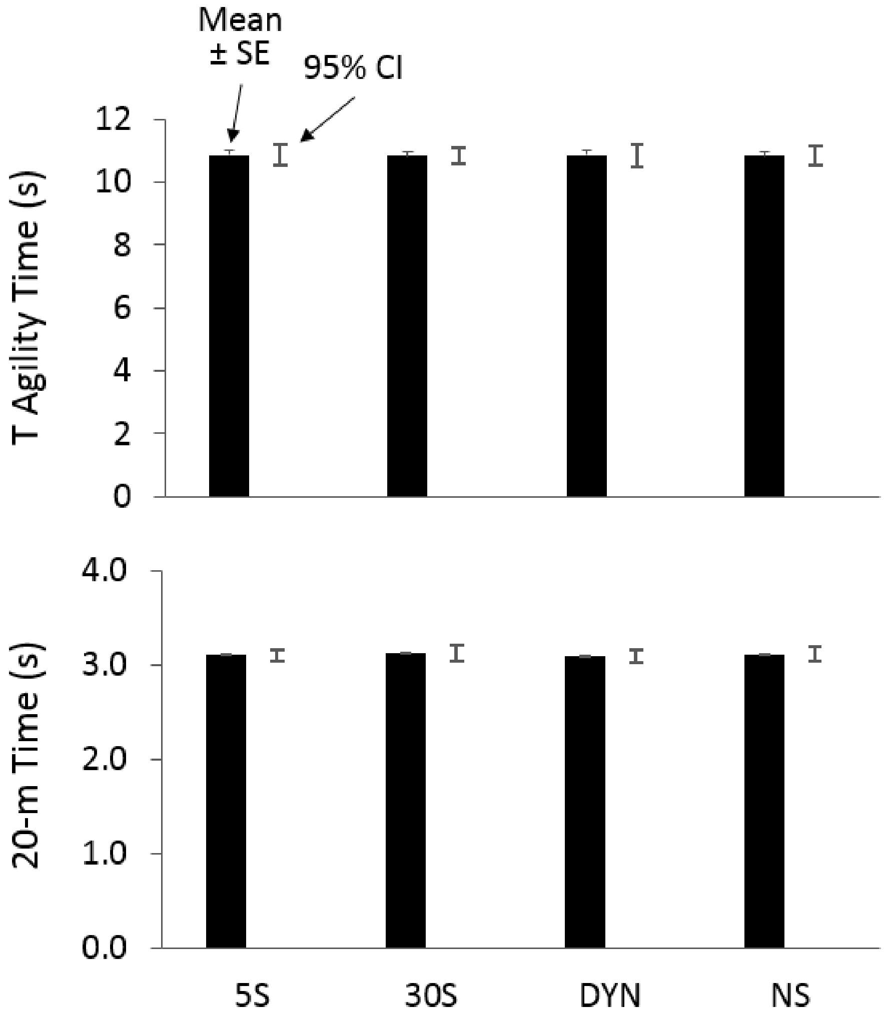

Figure 3. 20-m sprint run (bottom panel) and T agility (top panel) times recorded in 5S (5-s static stretch), 30S (30-s static stretch), DYN (dynamic stretch) and NS (no-stretch, control) conditions. There were no differences in test performances between the conditions. Shown are the mean ± SE (black column with error bar) and 95% confidence intervals of the mean (separate gray bar) jump performances.

Supplemental Digital Content 1. Stretch instructions and photo

A. Calves

Static

1. Assume push-up position, keeping knees and elbows straight.
2. Allow one knee to drop by rolling onto ball of foot.
3. Gently lower heel of planted foot down as low to the ground as possible until stretch is felt at the calf.
4. Hold the stretch at point of discomfort (POD) for 5 or 10 seconds (depending on instructions for the day) before switching legs.

Dynamic

1. Assume push-up position, keeping knees and elbows straight.
2. Allow one knee to drop by rolling onto ball of foot.
3. Gently lower heel of planted foot down as low to the ground as possible until stretch is felt at the calf.
4. Hold at POD only briefly (0.5 s) before lifting the heel up again.
5. Repeat for 5 repetitions per leg in a down-pause-up motion.

Performance points

1. Point grounded foot straight ahead
2. Keep the back straight.
3. Lower the heel as close to the ground as possible to POD.

B. Quadriceps

Static

1. Grasp ankle and gently pull your heel up and back until you feel the stretch in the front of your thigh.
2. Tighten your stomach muscles to prevent your stomach from sagging outward, and keep your knees close together.
3. Hold at POD for 5 or 10 seconds.
4. Switch legs and repeat.

Dynamic

1. Grasp ankle and gently pull your heel up and back until you feel the stretch in the front of your thigh.
2. Tighten your stomach muscles to prevent your stomach from sagging outward, and keep your knees close together.
3. Add a secondary pulling/tugging motion (pull foot upwards along your back) before releasing the ankle and switching legs.
4. Repeat for 10 repetitions per leg in an up-tug-down motion.

C. Hamstrings

Static

1. Lie on back and lift knee up, keeping knees straight as far as possible and maintaining dorsiflexion.
2. Grasp behind thigh near knee with both hands and pull knee close to chest.
3. Hold stretch for 5 or 10 seconds at POD.
4. Release and repeat with opposite leg.

Dynamic

1. Lie on back and lift knee up, keeping knees straight as far as possible and foot maintaining dorsiflexion.
2. Grasp behind thigh near knee with both hands and pull knee close to chest.
3. Add a secondary pulling/tugging motion before releasing leg.
4. Repeat with opposite leg, 5 repetitions per leg.

Performance points

1. Maintain foot dorsiflexion
2. Keep knee extended

D. Hip Flexors

Static

1. Stand with hands on hips and with one leg approximately a leg length in front of the other, with the forward leg slightly bent at the knees and rear leg maximally extended.
2. Slowly lunge forward by bending forward leg.
3. With chest high, straighten hip of rear leg by pushing hips forward.
4. Hold stretch at POD for 5 or 10 seconds and repeat with opposite side.

Dynamic

1. Stand with hands on hips and with one leg approximately a leg length in front of the other, with the forward leg slightly bent at the knees and rear leg maximally extended.
2. Slowly lunge forward by bending forward leg.
3. With chest high, straighten hip of rear leg by pushing hips forward.
4. Hold stretch at POD for about a second before returning to starting position.
5. Repeat for 5 repetitions in a ‘forward-pause-back’ motion before switching to opposite leg.

Performance points

1. Keep torso upright, close to vertical.

E. Hip Adductors

Static

1. Stand with feet facing forward and slightly more than shoulder width apart
2. Lean to one side by dropping one knee, causing the muscles of the other leg to go into tension
3. Hold the stretch for 5 or 10 seconds at POD
4. Switch legs and repeat.

Dynamic

1. Stand with feet facing forward and slightly more than shoulder width apart
2. Lean to one side by dropping one knee, causing the muscles of the other leg to go into tension
3. Pause and hold at stretch position at POD for about a second before leaning to the other side
4. Repeat for 5 repetitions per side in a ‘lean-pause-back’ motion.

Performance points

1. Maintain vertical upper body

F. Ankles

Static

1. Stand with hands on hips and feet shoulder-width apart.
2. Supporting bodyweight on one leg, roll ankle of other leg laterally until stretch is felt to POD.
3. Hold for 5 or 10 seconds.
4. Return and repeat with opposite ankle.

Dynamic

1. Stand with hands on hips and feet shoulder-width apart.
2. Supporting bodyweight on one leg, roll ankle of other leg laterally until stretch is felt to POD.
3. Hold stretch position for about a second before returning to starting position.
4. Repeat for 5 repetitions in a ‘roll-pause-back’ motion before switching legs.

G. Gluteals

Static

1. Standing on one leg, grasp below the knee of the other leg and pull it as close to your chest as possible.
2. Hold the stretch at POD for 5 or 10 seconds.
3. Release and repeat with other leg.

Dynamic

1. Standing on one leg, grasp below the knee of the other leg and pull it as close to your chest as possible.
2. Add a secondary tugging motion before releasing and switching legs.
3. Repeat for 5 repetitions per leg.

H. Upper chest and shoulder

Static

1. Interlock fingers of both hands behind your back, palms together, and lift both arms up and back as high as possible while maintaining full elbow extension.
2. Hold the stretch at POD for 5 or 10 seconds.

Dynamic

1. Interlock fingers of both hands behind your back, palms together, and lift both arms up and back as high as possible while maintaining full elbow extension.
2. Pause at stretch position for ~0.5 s before releasing.
3. Repeat for 5 repetitions in a stretch-pause-release motion.

Performance points

1. Minimize shoulder shrug

I. Upper back

Static

1. Interlock fingers of both hands in front of torso, palms together, and lift both arms forward and up until it is directly above your head.
2. Hold the stretch at POD for 5 or 10 seconds, feeling the stretch through the back muscles.

Dynamic

1. Interlock fingers of both hands in front of torso, palms together, and lift both arms forward and up until it is directly above your head.
2. Pause at stretch position for ~0.5 s before releasing, feeling the stretch through the back muscles.
3. Repeat for 5 repetitions in a ‘stretch-pause-release’ motion.