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Acute effects of dynamic stretching on knee joint position sense and dynamic balance in recreational runners: A randomized controlled trial

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ABSTRACT

Objectives: Proprioception and dynamic balance are crucial elements of neuromuscular control during running, supporting movement precision and postural adjustments. Dynamic stretching is commonly used in warm-ups to enhance muscle activation and sensorimotor readiness, but its acute effects on proprioception and balance remain unclear.
Design: Randomized controlled trial.
Participants: Sixty-two healthy recreational runners (25–45 years; $\geq$20 km/week), randomly assigned to a Dynamic Stretching group ($n = 31$) or a control group performing light walking ($n = 31$).
Main outcome measures: Joint position sense was assessed through active joint repositioning using 2D video analysis, with Absolute Angular Error, Relative Angular Error, and Variable Angular Error as outcomes. Balance was evaluated using the Y-Balance Test, including anterior, posteromedial, and posterolateral reach directions, as well as a composite score.
Results: The Dynamic Stretching group showed significant reductions in Absolute Angular Error ($p < 0.05$) and Variable Angular Error ($p < 0.001$), with a between-group difference in Relative Angular Error ($p = 0.043$). Both groups improved Y-Balance Test scores, but the Dynamic stretching group achieved significantly greater gains in posteromedial reach and Composite Score ($p < 0.001$).
Conclusions: Dynamic stretching acutely improves proprioceptive accuracy and dynamic balance in recreational runners, supporting its inclusion in warm-up routines.

1. Introduction

Running is one of the most practiced sports worldwide due to its accessibility and well-established health benefits, including improved cardiovascular fitness and reduced mortality [9,24]. However, optimal running performance depends not only on cardiovascular and muscular conditioning but also on neuromuscular control mechanisms that ensure coordination, postural regulation, and joint stability [8]. This study focuses on recreational runners, defined by Janssen et al. [20] as non-elite adults engaging in regular running practice given their high prevalence and heterogeneous warm-up routines in real-world settings

Proprioception integrates afferent information about joint position and movement to support postural regulation and motor accuracy during running. At the knee, joint position sense (JPS) is acutely modifiable by physiological state: brief warm-up procedures can improve knee position sense [25], whereas fatigue degrades it independent of the muscle group fatigued [38]. Experimental work confirms acute modulation of knee JPS with warm-up and fatigue [39], and stretching

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Abbreviations: AAE, Absolute Angular Error; BMI, Body Mass Index; CNS, Central Nervous System; CS, Composite Score; DS, Dynamic Stretching; JPS, Joint Position Sense; Kms, Kilometers; Min, Minutes; POD, Point of Discomfort; RAE, Relative Angular Error; ROM, Range of Motion; SD, Standard Deviation; SS, Static Stretching; VAE, Variable Angular Error; YBT, Y-Balance Test; 95 %CI, 95 % Confidence Interval.

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modality can also alter knee JPS [30]. Mechanistically, these short-term changes align with muscle spindle behavior and central integration of proprioceptive cues [34,35]. Importantly, recreational runners do not consistently exhibit superior proprioceptive control; similar or even poorer active joint position sense versus non-runners has been reported [19]. A plausible explanation is task specificity: the cyclic, low-variability nature of running may constrain sensorimotor diversity and proprioceptive refinement compared with multidirectional sports [31]. Deficits in joint position sense have been proposed to alter lower-limb kinematics, reduce running economy, and increase cumulative loading, thereby elevating overuse-injury risk in recreational runners [7]. More recently, empirical evidence has supported this rationale, showing that altered foot biomechanics can influence knee proprioception, with greater joint position errors and poorer balance performance [14].

Dynamic stretching (DS) has emerged as a preferred alternative to static stretching in warm-up routines. It involves active, controlled movements that elevate temperature and prime neuromuscular function. Early work characterized mechanisms and dose features [12] and a broad synthesis detailed acute effects and protocol variables [3]. In endurance contexts, findings for running-related performance are mixed [11]. For proprioception and dynamic balance, recent reviews highlight inconsistent results, likely reflecting protocol heterogeneity and especially the timing of DS within the warm-up [49,6]. Consistent with this variability, some studies report acute improvements in balance/proprioceptive outcomes after DS [1], whereas others show limited or mixed effects [6]. Dynamic balance in running largely depends on keeping the knee stable during single-leg stance and gait transitions. The Y-Balance Test (YBT) provides reliable and practically useful assessment, with evidence of discriminant and predictive utility in active populations [33]. YBT performance reflects how well runners maintain knee alignment and control load on a single limb [27] and is supported by proximal control, particularly hip strength/activation [23]. Compared with light walking, DS provides joint-angle–specific afferent stimulation and greater neuromuscular priming, which can acutely sharpen knee JPS and single-leg control [3]. Collectively, these factors mean the acute effects of DS on knee JPS and dynamic balance in recreational runners remain insufficiently characterized. In this context, we standardized key protocol features: a tested a brief (~5 min), lower-limb, multi-segment DS performed immediately before assessment and contrasted it with an active, low-neural-priming comparator (light walking at RPE 1–3).

Therefore, the aim of this study was to examine whether a dynamic stretching-based warm-up protocol acutely improves knee joint position sense and dynamic balance in recreational runners. We hypothesized that, relative to light walking, the dynamic-stretching warm-up would reduce knee joint position sense errors - namely lower AAE (greater accuracy), lower VAE (greater consistency), and RAE values closer to zero (reduced directional bias) - and would improve dynamic balance, evidenced by higher Y-Balance Test reach distances in the anterior, posteromedial, and posterolateral directions and a higher composite score.

2. Materials and methods

2.1. Study design, randomization and blinding

This was a randomized, controlled, repeated-measures trial with a parallel-group design and repeated measures (pre- and post-intervention). After an online screening questionnaire (demographics and training background) and confirmation of eligibility, participants were allocated 1:1 to a dynamic stretching (DS) group or a control group (light walking) using a computer-generated random sequence prepared by an external collaborator not involved in enrollment or testing. Allocation was concealed with opaque, sealed, identical envelopes. Before each assignment, envelopes were shuffled and laid out on a table; the participant picked one envelope after eligibility confirmation and after baseline measurements were completed, and the envelope was then opened by the study coordinator. Envelopes were sequentially numbered. The outcome assessor was not blinded to group assignment.

2.2. Setting and study duration

Data collection took place in a quiet, controlled indoor environment between December 2024 and March 2025. The room was maintained at 20–22 °C with a non-slip surface. Participants were tested barefoot. Environmental conditions were kept constant across all participants.

2.3. Participants

Participants were classified as recreational runners using the following operational definition: adults running $\geq$ 3 sessions·week^{-1} with a weekly volume $\geq$ 20 km for $\geq$ 6 months, without professional/elite involvement [20]. This ensured a homogeneous, non-elite endurance cohort with consistent exposure to running-related neuromuscular stimuli.

Sixty-two healthy recreational runners aged 25–45 years were recruited through local running clubs and screened for eligibility. Restricting the sample to healthy individuals minimized confounding from injury- or disease-related proprioceptive and balance impairments (e.g., recent lower-limb injury/surgery, neurological/vestibular disorders, medications affecting sensorimotor function) and ensured a homogeneous cohort to detect acute intervention effects.

Inclusion criteria were: (1) regular running practice ($\geq$3 sessions/week and >20 km/week for at least 6 months); and (2) no injuries limiting training within the past 6 months. Exclusion criteria included: (1) history of neurological or vestibular disorders; (2) cardiovascular or congenital pulmonary conditions; (3) major lower-limb injuries or surgeries in the previous 12 months; and (4) intense physical activity in the 48 h prior to testing.

Pre-test activity control. Participants confirmed no vigorous physical activity in the prior 48 h using a standardized checklist at arrival (compliance was self-reported).

2.4. Sample size calculation

An a priori power analysis (G*Power 3.1.9.7) was conducted for our primary analysis (two-way mixed ANOVA, group × time; $\alpha = 0.05$; power = 0.80). The expected effect size was taken from Romero-Franco and Jiménez-Reyes [39], who examined acute warm-up/fatigue effects on knee joint position sense (AAE/RAE/VAE) in healthy, physically active adults using a comparable protocol. Using an effect size of $d = 0.733$, the required sample was 31 participants per group ($N = 62$).

2.5. Procedures

Participants completed an online questionnaire with demographic and training background information. After eligibility was confirmed (randomization details in 2.1 Study Design, Randomization and Blinding), each participant underwent pre-intervention assessments, performed the assigned intervention, and then completed post-intervention assessments within the same visit. The DS group performed a 5-minute dynamic stretching protocol targeting five lower-limb muscle groups. The control group walked on a treadmill at a self-selected light pace (1–3 on the Modified Borg Scale), as referenced by Jesus et al. [21].

Both groups were assessed immediately before and after the intervention for two outcomes: knee joint position sense (JPS) and dynamic balance (Y-Balance Test). All assessments were conducted under standardized conditions by the same assessor to ensure consistency and minimize measurement bias under the conditions described in 2.2 Setting and Study Duration.

2.6. *Intervention protocol*

The DS protocol was based on Faelli et al. [11] and included five dynamic stretching exercises, each performed bilaterally for 30 s in a continuous, controlled, and rhythmic manner (see Fig. 1):

- **Dynamic quadriceps stretch with active hip extension in single-leg stance**
  From a standing position, the participant flexed the knee, bringing the heel toward the glutes while maintaining core activation and pelvic alignment. Movements alternated between legs in a fluid back-and-forth pattern emphasizing posture control.
- **Dynamic hamstring stretch with knee extension in supine position**
  In a supine position, the participant actively flexed the hip while extending the knee and dorsiflexing the ankle. The hands supported the posterior thigh. Movements followed a smooth rhythm targeting the posterior chain.
- **Dynamic hip flexor stretch with forward trunk lean**
  From a wide-stance lunge position, the participant leaned the trunk forward while keeping the rear leg extended. The movement was repeated with alternate leg transitions.
- **Dynamic adductor stretch with lateral weight shift**
  Standing with feet wider than shoulder width, the participant shifted weight laterally, flexing one knee while keeping the opposite leg extended, alternating sides in a continuous motion.
- **Dynamic gluteus stretch with single-leg hip flexion**

While balancing on one leg, the participant flexed the opposite hip and knee, pulling the knee toward the chest in a controlled alternating pattern, maintaining postural stability.

Movements were executed within each participant's active range of motion, targeting the point of discomfort (POD), defined as a mild, pain-free stretch. POD was self-monitored using a 0–10 subjective scale [4].

The DS protocol lasted approximately 5 min and was supervised by a licensed physiotherapist to ensure correct technique, rhythm, and intensity. The control condition consisted of 5 min of treadmill walking at a self-selected light pace corresponding to RPE 1–3 on the Modified Borg scale, with RPE checked each minute [21]. All sessions were supervised by a licensed physiotherapist.

2.7. *Outcome measures*

2.7.1. *Joint position sense (JPS)*

Knee JPS was assessed using an active joint repositioning test in a closed kinetic chain, following established methods [25,38]. Participants attempted to replicate a target knee flexion angle between 40° and 60° without visual feedback. Three repositioning attempts were recorded. After a standardized familiarization (three practice trials), they completed three reproduction attempts, selected to balance precision with feasibility in a single, acute pre–post session and consistent with 2D marker-based protocols reporting acceptable reliability [17].

A Full HD digital camera (1920 ×1080p, 30fps) was positioned perpendicular to the sagittal plane, 7 m away at knee height. Reflective markers were placed on the greater trochanter, lateral femoral condyle, fibular head, and lateral malleolus to define thigh and shank axes for angle calculation via 2D motion analysis.

Recordings were analyzed with Kinovea software (v0.8.15), validated for 2D clinical angle assessment [18,36]. Variables calculated were:

- **Absolute Angular Error (AAE):** absolute difference (in degrees) between reproduced and target angle — overall accuracy; lower values = greater accuracy.
- **Relative Angular Error (RAE):** algebraic difference — directional bias; positive = overshoot, negative = undershoot; values closer to zero = less directional bias (better).
- **Variable Angular Error (VAE):** standard deviation across three trials — consistency of performance; lower values = greater consistency.

2.7.2. *Dynamic balance (Y-Balance Test)*

Dynamic balance was assessed with the Lower Quarter Y-Balance Test, a reliable tool for functional postural evaluation [40,32]. Participants stood barefoot on the dominant leg, as identified in the initial screening questionnaire (self-reported preferred kicking leg), on the platform and reached in the anterior (ANT), posteromedial (PM), and posterolateral (PL) directions with the contralateral leg.

After three familiarization trials per direction, participants performed three recorded trials per direction; the longest valid reach was used for analysis. Trials were repeated if balance was lost, the hands left the hips, or the reaching foot failed to return to the starting position [2]. Anterior reach was corrected for foot length as per lab protocol. Reach distances were normalized to leg length of the tested limb (anterior superior iliac spine to distal tip of the medial malleolus) and expressed as percentages. A composite score (CS) was calculated by averaging the three normalized directions. The composite score (CS) was calculated as the mean of the three normalized reach directions [40], using the formula:

$$\textit{Composite Score}(CS) = \frac{ANT + PM + PL}{3 \quad * \textit{Leg Length}} * 100$$

Note that Y-Balance outcomes are reported as medians [IQR] in Section 3 (Results) because normalized reach distances showed non-normal, skewed distributions based on Shapiro–Wilk tests and visual inspection.

2.8. *Data management, ethical approval and consent*

Data handling followed GDPR-compliant procedures. All datasets were de-identified and stored securely in encrypted files with restricted access. Video data were processed offline using Kinovea (version specified in Methods), and only anonymized outputs were used for analysis.

Ethical approval and consent. The protocol was approved by the Ethics Committee of the Polytechnic Institute of Leiria (protocol CE/IPLEIRIA/75/2024, 18 July 2024) and conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent prior to enrollment and data collection.

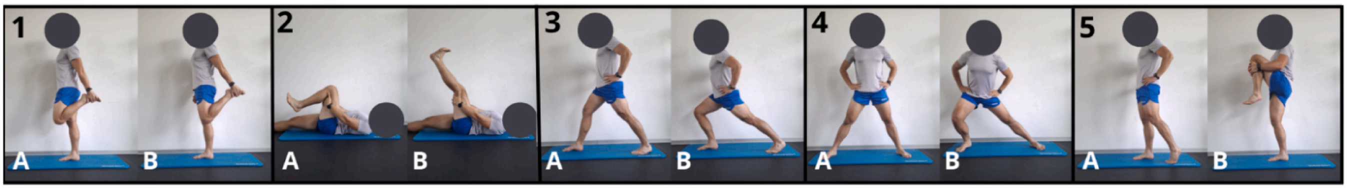

Fig. 1. Start (A) and end (B) positions of the five dynamic stretching exercises performed by the experimental group: (1) quadriceps stretch with active hip extension in single-leg stance; (2) hamstring stretch with knee extension in supine position; (3) hip flexor stretch with forward trunk lean; (4) adductor stretch with lateral weight shift; and (5) gluteus maximus stretch with single-leg hip and knee flexion.

Fig. 2. Assessment of knee joint position sense. Images show the initial position (A) and the active movement toward the target range (40–60°) (B) used to evaluate joint angle reproduction. Black dots indicate the placement of anatomical markers used for video.

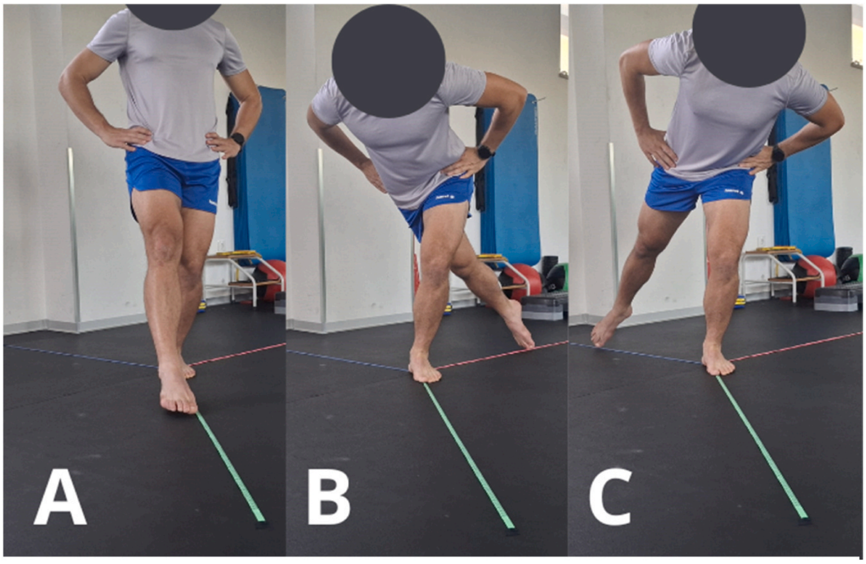

Fig. 3. Y-Balance Test (YBT) protocol. The images illustrate the execution of the test in the anterior (A), posteromedial (B), and posterolateral (C) reach directions.

2.9. Statistical analysis

Statistical analyses were conducted using IBM SPSS Statistics version 26.0. Data distribution was tested with the Shapiro–Wilk test. Knee JPS variables (normal distribution) were analyzed using paired and independent samples *t*-tests; YBT variables (non-normal distribution) were analyzed using the Wilcoxon signed-rank test and Mann–Whitney *U* test. Given the acute exploratory nature of this study and the correlated outcomes, p-values are reported unadjusted; results are interpreted alongside effect sizes and 95 % confidence intervals to avoid over-conservative inference from multiple testing. *We did not perform a formal group×time interaction analysis (e.g., mixed ANOVA or mixed-effects models) because several outcomes violated normality and the sample size was modest; instead, we prioritized distribution-appropriate pairwise tests to preserve statistical assumptions and provide transparent magnitude estimates. Between-group differences were tested on the change scores (Δpost–pre) unless otherwise stated.*

We report two-sided p-values ($\alpha = 0.05$), effect sizes derived from test statistics (paired t: Cohen's $d_{(Z)} = t/\sqrt{n}$; independent t: Cohen's $d = t\sqrt{(1/n_1 + 1/n_2)}$; Wilcoxon/Mann–Whitney: $r = |Z|/\sqrt{N}$), with magnitude classified as small (0.2/0.1), moderate (0.5/0.3), or large (0.8/0.5) for d/r, respectively. We provide 95 % confidence intervals for point estimates (means ± SD or medians [IQR]) and, where available, for pre–post changes.

Because distributional properties differed by outcome, JPS variables that met normality assumptions (Shapiro–Wilk) are reported as means ± SD, whereas Y-Balance variables violated normality and are therefore summarized as medians [IQR]. This mixed reporting reflects the scale and distribution of each family of outcomes and avoids biased parametric summaries for skewed data.

3. Results

3.1. Participant characteristics

Table 1A presents the continuous baseline characteristics of the sample. No significant differences were found between the control and experimental groups in age (35.1 ± 5.6 vs. 35.2 ± 5.7 years; $p = 0.965$), height (172.6 ± 8.7 vs. 175.5 ± 6.6 cm; $p = 0.137$), or body mass (73.1 ± 11.1 vs. 76.2 ± 11.7 kg; $p = 0.290$). Body mass index (BMI) was also comparable between groups (24.5 ± 2.8 vs. 24.6 ± 2.6 kg/m^2; $p = 0.885$).

Regarding training experience, no significant differences were observed in years of running practice (5.6 ± 3.8 vs. 4.4 ± 2.7 years; $p = 0.170$), indicating that both groups were equivalent at baseline in anthropometric and training-related variables.

Table 1B summarizes the qualitative characteristics of the participants. Sex distribution was balanced across groups, with a predominance of male participants in both (74.2 % in the control group vs. 77.4 % in the experimental group; $p = 0.767$). Although a higher proportion of left-leg dominant individuals was observed in the experimental group (32.3 % vs. 16.1 %), this difference was not statistically significant ($p = 0.138$).

Most participants fell within the 20–34 km weekly training range, and road surfaces were the most commonly reported training surface, both habitual and preferred. No significant differences were found between groups regarding training preferences or patterns ($p > 0.05$ for all comparisons).

Slight differences were noted in warm-up strategies, with the experimental group reporting more frequent use of dynamic stretching and plyometric exercises. Nonetheless, light jogging remained the most commonly used warm-up method overall. Most participants reported warm-up durations between 6 and 10 min. A similar proportion of participants in each group reported sustaining a running-related injury in the past year ($p = 0.783$).

3.2. Joint position sense outcomes

Joint position sense results are presented in Tables 2A 2B.

Within-group analysis (Table 2A) showed significant pre–post reductions in AAE and VAE in both groups. Changes were larger in the dynamic-stretching group (AAE: $p < 0.001$, $d_{(z)} \approx 1.09$, large; VAE: $p < 0.001$, $d_{(z)} \approx 0.75$, moderate-to-large), while the control group also improved (AAE: $p = 0.002$, $d_{(z)} \approx 0.60$, moderate; VAE: $p = 0.006$, $d_{(z)} \approx 0.54$, moderate).

For RAE (signed error; closer to 0 = better), a within-group shift toward zero occurred in the control group ($p = 0.002$, $d_{(z)} \approx 0.62$, moderate), whereas no significant change was observed in the dynamic-stretching group ($p = 0.341$, $d_{(z)} \approx 0.17$, small).

Between-group comparisons of change scores (Table 2B) showed a significant difference for ΔRAE favoring dynamic stretching (mean difference = 1.20° [95 % CI 0.04, 2.44], $p = 0.043$, $d \approx 0.53$, moderate). For ΔAAE and ΔVAE, between-group differences were not significant ($p > 0.05$) and the standardized effects were small ($d \approx 0.24$ in both).

Table 1A
Baseline characteristics of the sample by group, including anthropometric and training variables (mean ± standard deviation).

Variable	Control (n = 31)	Experimental (n = 31)	*p*-value
Age (years)	35.1 ± 5.6	35.2 ± 5.7	0.965
Height (cm)	172.6 ± 8.7	175.5 ± 6.6	0.137
Body mass (kg)	73.1 ± 11.1	76.2 ± 11.7	0.290
BMI (kg/m^2)	24.5 ± 2.8	24.6 ± 2.6	0.885
Years of running practice	5.6 ± 3.8	4.4 ± 2.7	0.170

BMI = Body Mass Index; *p* < 0.05 was considered statistically significant (Student's *t*-test for independent samples).

Table 1B
Qualitative characterization of the sample.

Variable	Control (n = 31)	Experimental (n = 31)	*p*-value[1]
Sex			0.767
Male	23 (74.2 %)	24 (77.4 %)	
Female	8 (25.8 %)	7 (22.6 %)	
Dominant Leg			0.138
Right	26 (83.9 %)	21 (67.7 %)	
Left	5 (16.1 %)	10 (32.3 %)	
Weekly Training Volume			0.387
20–34 km	15 (48.4 %)	19 (61.3 %)	
35–50 km	12 (38.7 %)	7 (22.6 %)	
Over 50 km	4 (12.9 %)	5 (16.1 %)	
Habitual Training Surface			0.574
Road	26 (83.9 %)	26 (83.9 %)	
Trail	4 (12.9 %)	5 (16.1 %)	
Mountain	1 (3.2 %)	0 (0.00 %)	
Preferred Training Surface			0.788
Road	13 (41.9 %)	15 (48.4 %)	
Trail	11 (35.5 %)	11 (35.5 %)	
Mountain	7 (22.6 %)	5 (16.1 %)	
Warm-Up Type			0.149
Walking	1 (3.2 %)	1 (3.2 %)	
Light Jogging	22 (71.0 %)	15 (48.4 %)	
Static Stretching	3 (9.7 %)	3 (9.7 %)	
Dynamic Stretching	1 (3.2 %)	5 (16.1 %)	
Plyometrics	0 (0.00 %)	4 (12.9 %)	
Technique Drills	4 (12.9 %)	3 (9.7 %)	
Warm-Up Duration			0.269
Less than 5 min	10 (32.3 %)	17 (54.8 %)	
6–10 min	15 (48.4 %)	11 (35.5 %)	
11–15 min	5 (16.1 %)	3 (9.7 %)	
16–20 min	1 (3.2 %)	0 (0.00 %)	
Injury in the Past Year			0.783
Yes	21 (67.7 %)	22 (71.0 %)	
No	10 (32.3 %)	9 (29.0 %)	

[1] Chi-square test (χ^2); $p < 0.05$ considered statistically significant. Values are presented as absolute frequency followed by the percentage (%) relative to the group (n = 31), reflecting the representativeness of each category in the control and experimental groups.

3.3. Y-balance test outcomes

Within-group analysis (Table 3A) indicated significant post-intervention increases in all reach directions and in the composite score for both groups. In the control group, improvements were observed in the anterior (+1.11 %; $p = 0.007$), posteromedial (+4.12 %; $p < 0.001$), and posterolateral (+1.84 %; $p < 0.001$) directions, as well as in the composite score (+3.20 %; $p < 0.001$) with moderate-to-large effect sizes across all outcomes.

The dynamic stretching group exhibited greater gains in all directions: anterior (+3.37 %; $p < 0.001$), posteromedial (+7.41 %; $p < 0.001$), posterolateral (+6.24 %; $p < 0.001$), and composite score (+5.84 %; $p < 0.001$), with moderate to large effect sizes across all outcomes.

Between-group comparisons (Table 3B) revealed statistically significant differences favoring the dynamic stretching group in the posteromedial direction (median difference = +5.75 %; $p < 0.001$) and in the composite score (median difference = +3.64 %; $p < 0.001$). No significant between-group differences were observed in the anterior ($p = 0.095$) or posterolateral ($p = 0.095$) directions. Effect sizes for PM and Composite were moderate-to-large.

Table 2A
Knee Joint Position Sense before and after intervention, percentage change, and within-group comparisons.

Variable	Group	Pre-Mean (±SD)	Post-Mean (±SD)	Δ % (Mean ± SD %)	*Within-Group* Difference (95 % CI) (°)	*p*-value	Cohen's $d_{(z)}$
AAE (°)	Control	2.85 ± 1.10	2.02 ± 0.78	−17.2 % ± 48.4 %	−0.8 [−1.33, −0.33]	0.002	0.60 (moderate)
	Experimental	2.84 ± 1.06	1.71 ± 0.67	−32.5 % ± 34.6 %	−1.1 [−1.76, −0.50]	< 0.001	1.09 (large)
RAE(°)	Control	−0.93 ± 1.90	0.68 ± 1.50	136.7 % ± 392.5 %	+ 1.6 [+ 0.64, + 2.58]	0.002	0.62 (moderate)
	Experimental	−0.63 ± 1.66	−0.26 ± 1.21	−70.5 % ± 329.8 %	+ 0.4 [−0.41, + 1.15]	0.341	0.17 (small)
VAE (°)	Control	2.43 ± 1.18	1.59 ± 0.83	−10.7 % ± 74.8 %	−0.8 [−1.42, −0.26]	0.006	0.54 (moderate)
	Experimental	2.52 ± 1.49	1.31 ± 0.79	−5.5 % ± 132.8 %	−1.2 [−1.89, −0.53]	< 0.001	0.75 (moderate-to-large)

Values are presented as mean ± standard deviation. AAE = absolute angular error; RAE = relative angular error (signed; closer to 0 = less directional bias); VAE = variable angular error; SD = standard deviation; Δ % = percentage change between pre- and post-intervention mean; *p*-value = statistical significance level of the paired-samples *t*-test; Cohen's *d* = effect size; Magnitude effect: small d 0.20 / r 0.10; moderate 0.50 / 0.30; large ≥ 0.80 / ≥ 0.50.); Control Group (n = 31); Experimental Group (n = 31).

Table 2B
Between-group comparisons of angular error changes (Δ) after the intervention.

Variable	Δ Control (±SD)	Δ Experimental (±SD)	Between-Group Difference (95 % CI)	*p*-value	Effect size (Cohen's d)
AAE (°)	−0.83 ± 1.39	−1.13 ± 1.04	0.3 [−0.32; 0.92]	0.337	0.24 (small)
RAE(°)	+ 1.61 ± 2.59	+ 0.37 ± 2.10	1.2 [0.04; 2.44]	0.043	0.53 (moderate)
VAE(°)	−0.84 ± 1.60	−1.22 ± 1.63	0.4 [−0.44; 1.20]	0.361	0.24 (small)

Δ = difference between post- and pre-intervention moments; AAE = absolute angular error; RAE = relative angular error; VAE = variable angular error; SD = standard deviation; 95 % CI = 95 % confidence interval for between-group differences; *p*-value = significance level of the independent samples *t*-test; Effect size (Cohen's d) with magnitude labels: small 0.20, moderate 0.50, large ≥ 0.80. RAE is a signed error; values closer to 0 indicate less directional bias (better).

Table 3A
Within-group comparisons (pre- vs. post-intervention) of *Y-Balance Test* results, expressed as median (IQR).

Variable	Group	Pre-Intervention	Post-Intervention	*r* *(magnitude)*	*p*-value
YBT A	Control	81.61 [77.59–87.74]	82.72 [81.27–86.72]	0.483 (moderate)	0.007
	Experimental	80.33 [78.06–83.77]	83.70 [81.77–85.59]	0.704 (large)	< 0.001
YBT PM	Control	86.52 [75.16–92.19]	90.64 [77.13–96.67]	0.806 (large]	<0.001
	Experimental	79.07 [76.44–84.57]	86.48 [77.63–92.04]	0.852 (large]	<0.001
YBT PL	Control	94.01 [84.74–100.39]	95.70 [89.46–102.69]	0.641 (large)	< 0.001
	Experimental	87.86 [86.32–99.69]	94.10 [89.46–100.35]	0.845 (large)	< 0.001
YBT CS	Control	87.51 [80.54–92.31]	90.39 [86.46–94.26]	0.869 (large)	< 0.001
	Experimental	82.67 [81.73–86.50]	88.51 [83.63–94.26]	0.866 (large)	< 0.001

YBT A = anterior direction; YBT PM = posteromedial direction; YBT PL = posterolateral direction; YBT CS = composite score; IQR = interquartile range; r = effect size ($r = |Z|/\sqrt{N}$) with magnitude thresholds: small 0.10, moderate 0.30, large ≥ 0.50; p < 0.05 was considered statistically significant. Values are medians [IQR] normalized to limb length (%). Within-group comparisons used the Wilcoxon signed-rank test (two-sided, α = 0.05). Because only aggregate pre/post summaries were available, 95 % CIs for the paired change (Δ) were not estimable; interpretation relies on r and p-values.

Table 3B
Between-group comparison of reach gains in the *Y-Balance Test* and composite score.

Variable	Control Group	Experimental Group	Absolute Difference	*r* *(magnitude)*	*p*-value
YBT A	0.78 [0.00–2.33]	1.57 [0.39–4.22]	+ 0.79	0.211 (small)	0.095
YBT PM	3.24 [1.85–5.35]	8.99 [4.87–12.72]	+ 5.75	0.493 (moderate-to-large)	< 0.001
YBT PL	1.92 [0.00–5.65]	3.97 [1.53–7.62]	+ 2.05	0.212 (small)	0.095
YBT CS	2.54 [1.52–4.17]	6.18 [3.87–7.49]	+ 3.64	0.488 (moderate-to-large)	< 0.001

YBT A = anterior direction; YBT PM = posteromedial direction; YBT PL = posterolateral direction; YBT CS = composite score; Absolute Difference = difference in reach gains between groups (experimental – control); r = effect size with magnitude thresholds: small 0.10, moderate 0.30, large ≥ 0.50.; p-value = statistical significance from the Mann–Whitney *U* test (two-sided, α = 0.05); values expressed as median (interquartile range). All values are normalized to limb length and expressed as percentages (%).

4. Discussion

This study examined the acute effects of a dynamic stretching (DS) protocol on knee joint position sense (JPS) and dynamic balance in recreational runners. The findings revealed consistent improvements in both domains, with clear improvements in proprioceptive variability and the more demanding directions of the Y-Balance Test (YBT), supporting DS as a facilitator of immediate neuromuscular readiness. Baseline data indicated group homogeneity in demographic and training characteristics, including sex, lower-limb dominance, weekly running volume, warm-up habits, training surfaces, and injury history. This supports the internal validity of the intervention and strengthens the interpretation of effects as attributable to the experimental condition.

We used a brief (~5 min) DS block immediately before testing to target acute readiness while avoiding fatigue and to keep exposure time-matched to the control. Evidence indicates that short, active warm-up elements (including DS) can yield small-to-moderate benefits when activity follows within minutes, and contemporary guidance emphasizes active preparations that raise temperature and neural readiness without decrements associated with prolonged static holds [3]. For ecological validity, we chose an active comparator: recreational runners typically transition via low-intensity locomotion rather than rest, so we used light treadmill walking (RPE 1–3, monitored each minute) to equate time and thermoregulatory effects while keeping neural priming low [21,3].

Regarding JPS, the DS protocol induced acute improvements in accuracy, consistency, and directional control of joint repositioning. These outcomes were expressed differently across the three analyzed parameters—absolute angular error (AAE), variable angular error (VAE), and relative angular error (RAE)—allowing a multidimensional interpretation of proprioceptive responsiveness. As highlighted by Romero-Franco and Jiménez-Reyes [39], proprioception is a multicomponent construct requiring distinct indicators to capture sensorimotor adaptations.

AAE, which reflects the accuracy of repositioning relative to a target angle, significantly decreased in the experimental group, with a large effect size (d = 1.04). This suggests that DS elicited immediate improvements in sensorimotor precision, likely mediated by activation of muscle spindles—mechanoreceptors sensitive to stretch that inform the central nervous system (CNS) about muscle length and velocity [35,3,41]. Although intergroup differences were not statistically significant, the experimental group exhibited a more stable improvement pattern, potentially reflecting enhanced sensory integrity and fine motor control even under acute stimulus conditions [37]. Similar findings were reported by Harry-Leite et al. [17], who observed a 56 % reduction in repositioning error following a single session of proprioceptive training.

Among the proprioceptive metrics, VAE appeared most sensitive to the intervention, showing a clear reduction and a moderate-to-large effect size (d = 0.75). Lower variability between trials suggests more stable and automated motor control, potentially reflecting implicit adaptation supported by cumulative sensory input [45]. High variability may indicate sensory disorganization and reduced motor quality [26,43]. DS likely promotes a neurophysiological context favorable to stabilization, by increasing range of motion, reducing muscle stiffness, and enhancing joint position perception [6]. These mechanisms align with Winter et al. [48], who reported average improvements of 46 % in proprioceptive acuity and 45 % in motor consistency after active movement-based interventions.

RAE, which incorporates error direction and reflects sensory bias in joint position perception, did not change significantly in the experimental group. Nonetheless, a trend toward directional correction was observed, with values approaching zero, suggesting refinement in proprioceptive perception. In contrast, the control group exhibited an inversion pattern in RAE, potentially reflecting transient sensory recalibration triggered by low-intensity neuromuscular stimulation, such as light walking. According to Tsay et al. [45], such behavior may indicate inefficient sensorimotor schema reorganization.

Taken together, a large within-group effect for AAE and a moderate-to-large effect for VAE indicate meaningfully greater accuracy and consistency of knee angle reproduction after DS. RAE, a signed error (positive = overshoot; negative = undershoot), tended to shift toward zero, indicating less directional bias (better). For runners, smaller errors, reduced variability, and less bias plausibly support steadier single-leg alignment during stance/transition, relevant to movement economy and cumulative joint loading [7], and recent work shows that distal biomechanical alterations can propagate to knee proprioception and balance [14]. Although between-group differences for ΔAAE and ΔVAE were small and non-significant, ΔRAE showed a moderate advantage for dynamic stretching. This pattern is compatible with limited power/-variability in an acute, single-session design and warrants confirmation in larger or repeated-session trials with minimally important change benchmarks for JPS.

The Proprioceptive Realignment Model (PReMo) proposes that the CNS minimizes discrepancies between perceived state and motor goal by adjusting postural perception in response to sensory input. In conditions of insufficient proprioceptive activation, directional instability may result from imprecise sensory realignment [45]. When inversion occurs without concurrent improvement in other proprioceptive parameters, it is interpreted as a marker of central sensory instability [35,3]. The stable RAE in the experimental group suggests that DS preserved internal sensory map integrity, promoting reliable motor control.

Participants reported weekly running volumes between 20 and 34 km, indicating regular exposure to motor stimuli. Despite this, DS induced significant improvements in proprioceptive accuracy (AAE) and consistency (VAE), suggesting that habitual activity alone does not ensure optimal sensory stability. Targeted dynamic interventions appear necessary to elicit meaningful sensorimotor adaptations, reinforcing the utility of DS in promoting accuracy, repeatability, and directional control in joint positioning.

The YBT is a valid and reliable measure of dynamic postural control, integrating sensory, motor, and cognitive components. In this study, DS elicited significant improvements in YBT performance, particularly in the experimental group, suggesting acute optimization of neuromuscular function. These findings align with research linking YBT performance with functional capability and motor control efficiency [22,33].

To enhance comparison sensitivity, values were normalized to leg length as recommended [16,40]. The anterior reach direction improved in both groups but showed no between-group difference, possibly due to limited DS specificity for quadriceps activation. Literature indicates anterior reach responds better to localized eccentric or segmental interventions [15,42,44,46].

Conversely, the posteromedial direction showed marked improvement in the experimental group. This direction requires high intersegmental coordination and proximal motor control [16,27]. DS likely facilitated sensory feedback and proximal stability, optimizing output in this demanding task [29,3].

The posterolateral direction, involving external hip rotation and lateral trunk control, also improved more in the experimental group. This may reflect enhanced multisegmental activation and proprioception elicited by DS [23,6]. Although differences were not statistically significant, the trend supports the role of DS in improving lateral postural control.

The composite score (CS), a global marker of dynamic stability, improved in both groups, with greater gains in the experimental group. CS has been linked to performance in complex motor tasks and is considered a sensitive predictor of functional capacity [29,33,48]. DS may enhance CS by promoting proximal stabilizer activation, proprioceptive feedback, and mobility [10,13,22,49].

Large within-group effects and moderate-to-large between-group advantages for the posteromedial direction and composite score are consistent with short-term gains in single-leg control aligned with running demands (maintaining knee alignment and managing stance-limb load). While anterior reach improved in both groups - consistent with lower specificity to DS - the pattern and magnitude observed support DS as a practically relevant warm-up element for dynamic stability. These observations accord with recent literature [1,49,6].

Notably, 48.4 % of participants in the experimental group preferred trail running or irregular surfaces, which challenge stability and enhance neuromuscular responses [47]. This may have potentiated DS responsiveness, particularly in complex directions. In contrast, the predominance of road running (83.9 %) in the sample may explain lower responsiveness in less demanding directions.

Overall, findings indicate that DS induces acute neuromuscular adaptations with complementary expression in joint proprioception and dynamic balance. Improvements in AAE, VAE, and RAE reflect sensory optimization, which translates into enhanced functional performance, particularly in the YBT's more demanding components.

This supports DS as not only a preventive strategy but also a neuromuscular activation tool for improving functional readiness in recreational runners. Its simplicity and applicability make it particularly valuable in pre-exercise routines lacking structured priming.

Sample characteristics contextualize the findings. Within the experimental group, 29 % reported previous exposure to dynamic or plyometric methods—factors associated with improved proprioception and postural control [3]. Moreover, 48.4 % preferred training on irregular terrain, known to enhance neuromuscular responsiveness [6], potentially moderating the DS effect.

We report effect sizes alongside p-values to emphasize clinical magnitude rather than dichotomous significance. Large effects with non-significant p in this acute, modest-N design likely reflect sampling variability/limited power and merit replication with larger samples and/or repeated sessions.

Despite its strengths, this study has limitations. The sample was composed mostly of healthy recreational male runners, limiting generalizability to female, elite, or clinical populations. Sex-based neuromuscular differences warrant further exploration [5]. Geographical homogeneity may also have restricted training profile variability. Only the self-reported dominant limb was tested, which may limit extrapolation to bilateral or limb-asymmetry contexts.

From a methodological standpoint, deviations from the ideal 40°–60° knee flexion range in JPS testing were retained, focusing on relative error rather than absolute angle. This is supported by tolerance margins in the literature [28]. Limiting the assessment to the knee joint and static repositioning restricts extrapolation to dynamic conditions. In addition, movement speed during repositioning was not controlled with an isokinetic device; although standardized scripts were used, angular-velocity variability cannot be excluded. The assessor was not blinded to group allocation, introducing potential measurement bias despite standardized procedures and a pre-specified processing workflow. Knee angles were obtained via 2D video rather than 3D capture; while clinically valid, this approach is less precise for out-of-plane motion. Potential learning effects from repeated trials must also be considered.

The lack of a passive control group prevents isolating the effect of warm-up itself from the type of intervention. Additionally, only acute effects were studied, and injury history data were self-reported, lacking detail on severity and lateralization. For Y-Balance, non-normal distributions required Wilcoxon-based summaries (medians [IQR]); confidence intervals for paired changes (Hodges–Lehmann) were not computed here because individual paired differences were not available in the current workflow. Finally, the single-session design and sample size limit power for between-group contrasts despite large effect sizes in some outcomes; larger and/or repeated-session trials are needed to determine durability and clinical thresholds of meaningful change. Testing time-of-day was not standardized and no retention assessment was performed; thus, durability beyond the immediate post-test is unknown. Analyses were exploratory without a pre-registered primary outcome or multiplicity adjustment; future confirmatory trials should address this.

Future research should explore DS protocol variations, include subjective and physiological readiness markers, and extend analyses to running economy and fatigue resistance. Correlational modeling between proprioception and functional outcomes may offer deeper insights. The RAE signal inversion observed in the control group warrants further study as a potential marker of proprioceptive instability. Trials should also test sequencing and timing of DS within the warm-up and characterize the time-course of effects (e.g., 0–20 min post-intervention) to identify an optimal window. Pre-registered designs with a primary outcome and minimally important change thresholds for JPS and Y-Balance will enhance interpretability and statistical rigor.

5. Conclusions

This study suggests that a dynamic-stretching warm-up can acutely improve knee joint position sense - enhancing accuracy (lower AAE), consistency (lower VAE), and directional control (RAE shifts toward zero, indicating less overshoot/undershoot) - and can enhance dynamic balance in recreational runners. Greater gains in posteromedial reach and the composite Y-Balance Test score indicate that dynamic stretching may be more effective than light walking for immediate neuromuscular readiness. Integrating brief dynamic stretching into pre-exercise routines may help optimize functional stability.

Ethical approval

The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the Polytechnic Institute of Leiria, Portugal (protocol no. CE/IPLEIRIA/75/2024 – 18 July 2024).

Informed consent

Informed consent was obtained from all subjects involved in the study.

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CRediT authorship contribution statement

Marina Saraiva: Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Nuno Tavares:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Edgar Simões:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

None declared.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2025.110049.

Data availability

The data are available upon request.

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