ACUTE EFFECTS OF DYNAMIC AND PNF STRETCHING ON LEG AND VERTICAL STIFFNESS ON FEMALE GYMNASTS

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Abstract

*The purpose of the study was to investigate the acute effect of Dynamic (DS) and PNF stretching on leg (K_{leg}) and vertical stiffness (K_{vert}) on female gymnasts. Thirty-one female athletes from various types of gymnastics (artistic, rhythmic, team gymnastics) participated in this study ([Mean ± SD] age: 22.32 ± 3.35 years, height: 164.87 ± 4.96 cm, body mass: 57.20 ± 6.54 kg) performed 30 sec running bouts at 4.44 m *s-1, under 3 different stretching protocols (PNF, DS, and no stretching [NS]). The total duration in each stretching condition was 6 minutes, and each of the 4 muscle groups was stretched for 40 seconds. Leg and vertical stiffness values were calculated using the "sine wave" method. No significant influence of stretching type on Kleg and Kvert were found after DS and PNF stretching. However, significant changes were found in Fmax, Dy, flight time (tf), step rate (SR), and step length (SL) after DS and PNF stretching protocol, indicating that DS produced greater changes compared to PNF protocol.*

Keywords: *warm-up activities, kinematic, kinetic, gait.*

INTRODUCTION

In order to improve their physical and psychological preconditioning but also to reduce the risk of injury (Woods, Bishop, and Jones, 2007), athletes in various sports perform warm-up before their training or competition. The static (SS) and dynamic stretching (DS) as the most common forms of stretching in the warm-up with the resulting benefits on flexibility have been extensively documented (Dallas, Tsiganos, Tsolakis, Tsopani, Di Cagno, Smirniotou, 2014). Although there is no agreement on which of them is the most effective method in flexibility, it is widely accepted that DS utilizes movements that mimic the specific sport or exercise in an exaggerated yet controlled manner altering the musculotendinous system (MTS) (Herda, Costa, Walter-Herda, Valdez, and Crammer, 2013), therefore, altering stretch-shortening cycle (SSC) performance. DS involves controlled movements of the limbs within the ROM (Fletcher, 2010). However, there is no clear consensus on how stretching influences performance, with DS reported to both improve (Hough, Ross, Howatson, 2009) or reduce performance (Costa, Herda, Herda, and Cramer, 2014).

Many authors agree that during SSC activities, active muscles of the MTS are pre-stretched and absorb energy, part of which is temporarily stored in a series of elastic elements and later reutilized in the phase where the muscles act concentrically to enhance the maximum mechanical power produced during the concentric phase (Svantesson, Ernstoff, Bergh, and

Grimby, 1991). It has been shown that lower limb stiffness affects power production during an SSC skill in adults, indicating that those with a stiffer MTS might benefit from faster elastic recoil during the upward, concentric, phase of the skill (Arampatzis, Schade, Walsh, and Brϋggemann, 2001). Furthermore, the use of elastic energy that has been stored during SSC exercises is affected by an optimum level of musculotendinous stiffness (Belli and Bosco, 1992).

Previous findings examining male subjects report that DS has no positive effects on running performance at a moderate pace (Zourdos, Wilson, Sommer, Lee, Park, and Henning, 2012) and it does not change leg and vertical stiffness during submaximal running (Pappas, Paradisis, Exell, Smirniotou, Tsolakis, and Arampatzis, 2017).

Another form of stretching to improve flexibility is the proprioceptive neuromuscular facilitation stretching (PNF). There are two neuromuscular mechanisms involved in PNF movement patterns: (a) reciprocal inhibition refers to the contracting of the target muscle (TM) (agonist) and relaxing of the opposed muscle (OM) (antagonist) that facilitates muscle contraction, and (b) the inverse stretch reflex or the Golgi tendon reflex is the protective mechanism that causes a relaxation in the muscle if too much tension is produced. Active motion is used to arouse the reciprocal inhibition response, increasing the lengthening of the muscle (Holcomb, 2000). PNF stretching prior to exercise has been found to increase MTU stiffness (Rees, Murphy, Watsford, McLachlan, and Coutts, 2007). The acute effect of PNF stretching on performance showed contradictory results (Bradley et al., 2007; Dallas et al., 2014; Kay et al., 2015; Konrad et al., 2017; Manoel et al., 2008).

It is considered that PNF stretching can produce an increase in MTU stiffness which is believed to be linked to an increased ability to store and release elastic energy. PNF stretching involves SS and isometric contractions in a cyclical pattern to enhance joint ROM (Funk et al., 2003), with two common techniques being contract-relax (CR) and contract-relax agonist contract (CRAC) (Sharman, Cresswell, and Riek, 2006). Both methods (PNF, DS) have been shown to increase the range of movement (ROM) (Lucas and Koslow, 1984); however, it is debatable which method is the most effective (Hardy and Jones, 1986). The distinctive characteristic of PNF is a brief isometric contraction that, performed while the muscle is held on stretch, lasts between 5 and 10 seconds (Hindle et al., 2012; Leblebici, Yarar, Aydın, Zorlu, Ertaş, and Kıngır, 2017; Marek et al., 2005; Sa, Matta, Carneiro, Araujo, Novaes, and Oliveira, 2016) with some of them showing a reduction in stiffness (Sa et al., 2016) and others showing no significant changes. Maybe this isometric contraction may act as pre-activation resulting in a consequent increase in muscle strength.

A lot of studies used the spring mass model (SMM) to describe lower limbs stiffness (Blickhan, 1998; Pappas et al., 2017). Although stiffness is considered an important factor in running performance (Arampatzis et al., 2001), the acute effects of different stretching methods during training and competition on vertical and leg stiffness are not well known. No other studies have examined the acute effect of PNF stretching on vertical and leg stiffness. In gymnastics, performing vaults on the table horse and/or during an acrobatic series, e.g., rondat backward salto, or in rhythmic gymnastics during the preparatory phase of a gymnastics series, athletes need to acquire a great amount of horizontal velocity in a short time with a few strides allowing them to perform the exercises that follow. To the authors' knowledge, only one study (Pappas et al., 2017) has examined the influence of SS and DS on male physical education students' leg stiffness during running, concluding that DS has no influence on leg or vertical stiffness, even though it has been proposed that DS reduces MTU stiffness. Nevertheless, no studies have determined the effects of DS and PNF stretching on vertical and leg stiffness in the same setup. Thus, this study is the first that has examined and compared the effects of DS and PNF stretching on leg and vertical stiffness, i.e., the kinematic and kinetic variables during submaximal treadmill running on female gymnasts. A secondary purpose was to inform future warm-up protocols and physical preparation if there were benefits to PNF or DS. It was hypothesized that both PNF and DS would acutely change the leg and vertical stiffness during treadmill running.

METHODS

Thirty-one female participants from various types of gymnastics (artistic, rhythmic, team gymnastics) participated in this study ([Mean ± SD] age: 22.32 ± 3.35 years, height: 164.87 ± 4.96 cm, body mass: 57.20 ± 6.54 kg, training experience: 10.63 ± 4.96 years). All subjects were healthy and recreationally training 8 to 12 hours per week according to their gymnastics training course. No participants with any lower extremity injuries in the prior 4 months were included and none of them had any lower limb length asymmetry. Ethical approval was gained from the Research Ethics Committee of the National and Kapodistrian University of Athens, School of Physical Education and Sports Science, and each participant signed informed consent forms before testing.

We used a randomized, counterbalanced, within-subjects experimental design to compare the acute effects of dynamic stretching (DS) and PNF stretching on leg and vertical stiffness during treadmill running. The study carried out over the course of 4 visits on non-consecutive days and at the same time of the day. On the first visit, the familiarization with the stretching methods and exercises was performed. On the second, third and fourth visit, the subjects were randomly selected to perform one of 3 possible conditions: (a) PNF stretching (PNF), (b) dynamic stretching (DS); and (c) control (without stretching) (CON).

Stretching Protocols. During 3 laboratory visits, the subjects performed the PNF, DS or control protocols in random order.

Proprioceptive Neuromuscular Facilitation (PNF) stretching. PNF stretching incorporates SS and isometric contractions in a cyclical pattern to enhance joint ROM (Sharman et al., 2006). The PNF stretches used the “hold relax” method (HR) in which the target muscle (TM) was lengthened and held in that position while the participant contracted the TM to its maximum isometrically for 6 seconds (Sa et al., 2016) against manual resistance (applied by the researcher), followed by a 10-second passive stretch (Etnyre and Abraham, 1986). The participant flexed the dominant leg to a knee-joint angle of 90º. For the contract phase of the PNF stretch, a padded chair was placed beneath the foot so the participant could apply maximal isometric tension at a 90º knee-joint angle. Two repetitions of each stretching exercise for each muscle group were held for 10 seconds at a point of discomfort but not pain, as acknowledged by the participant. There was no rest between the two trials. Verbal encouragement was provided during each muscle activation. The average time of each stretching period was 4 minutes approximately.

Dynamic Stretching (DS). For DS, a technique similar to the procedures of a previous study (Pappas et al., 2017) was used.

PNF flexibility conditioning protocol

Quadriceps. For the contract phase of the PNF stretch, participants were sat on a padded desk and maximal isometric tension, against manual resistance applied by the researcher at a point of mild discomfort as acknowledged by the participant, with knee extensors muscle at a 135° knee-joint angle applied approximately for 6 seconds. After a period of 3 seconds relaxation, the participant, standing upright with one hand against a wall for balance, flexed the TM to a knee-joint angle to stretch knee extensors muscles for 10 seconds.

Hamstrings. For the contract phase of the PNF stretch, from supine position, the knee flexors of the TM were moved in a stretch position via hip flexion, as indicated verbally by the participant, while maintaining full knee extension and the foot dorsi-flexed to 90º. The participant's contralateral control limb was held in contact with the support surface. The participant then attempted to maximally activate the knee flexors and hip extensors of the preferred limb for 6 seconds. After a period of 3 seconds relaxation the participant activated the agonist muscle groups (knee extensors and hip flexors) of the TM for 10 seconds.

Hip extensors. For the contract phase of the PNF stretch, from prone position with hip joint at the end of an elevated surface, flexed hip of the TM approximately at 135º applying maximal isometric tension of hip extensors for 6 seconds. After a period of 3 seconds relaxation the participant flexed the preferred leg from supine position on hip and knee joint trying to approach the chest, stretching the hip extensors muscles for 10 seconds.

Plantar flexors: For the contract phase of the PNF stretch, from upright position, supporting the foot tip (tread) on the end of an elevated surface in dorsal flexion, the participant maintained maximal isometric tension of the plantar flexors against a manual resistance applied on the participant's shoulders by the researcher at a point of mild discomfort, as acknowledged by the participants, for 6 seconds. After a period of 3 seconds relaxation from the same position, the participant tried to bring the heels to the lowest position to stretch the plantar flexors muscles for 6 seconds.

No stretching. The participants sat for 6 minutes and did not perform any stretching.

Before each pre-test, participants completed a 5-minute warm-up on the treadmill at 2.22 m $\cdot s^{-1}$. They randomly performed 1 of the 3 stretching exercises (PNF, DS, and CON), followed by post-tests. All participants completed three warm-up conditions, performed on different days with 48 hours apart, in a counterbalanced order. During the pre-tests and post-tests, they performed 30-second running bouts at 4.44 m $\cdot s^{-1}$on a motorized treadmill at their preferred step rate and length. This submaximal speed was chosen as an average of the range of running speeds (3.33–6.67 m $\cdot s^{-1}$) used in previous studies (Morin, Dalleau, Kyrolainen, Jeannin, and Belli, 2005; Pappas et al., 2017). To calculate vertical and leg stiffness the method described by Morin et al. (2005) was used.

$$K_{vert} = F_{max} \cdot \Delta y_c^{-1}$$
$$F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c} + 1\right)$$
$$\Delta y_c = -\frac{F_{max} t_c^{\,2}}{m\pi^2} + g\frac{t_c^{\,2}}{8}$$

$$K_{leg} = F_{max} \cdot \Delta L^{-1}$$
$$\Delta L = L - \sqrt{L^2 - \left(\frac{vt_c}{2}\right)^2} + \Delta y_c$$

K_{vert} is the vertical stiffness; **K_{leg}**, the leg stiffness; **F_{max}**, the maximal ground reaction force during contact; **Δ_y**, the vertical displacement of the center of mass; **m**, the body mass; **t_f**, the flight time; **t_c**, the contact time; **ΔL**, the lower limb length variation; and **L**, the resting lower limb length.

Data Analysis. The Quintic Biomechanics v21 (Sutton, United Kingdom) software was used for the analysis of all video-recorded steps. The leg and vertical stiffness calculation were based on the method of "sine wave" as suggested by Morin et al. (2005). To calculate leg and vertical stiffness, the mean values of flight time and contact time of 10 consecutive steps were used, whereas for the estimation of step rate and step length the method by Paradisis and Cooke (2001) was applied.

The IBM SPSS (version 24) was used for the statistical analyses. The arithmetic mean, SD, and range were calculated for each variable and trial. Raw data were checked for normality using a Shapiro-Wilk test as the sample size was .50. To explore the impact of time (pre-stretching and post-stretching) and condition (PNF, DS, and CON) on the dependent variables, a 2-way (time 3 condition) repeated measures analysis of variance was used for the statistical analyses. Sphericity was checked using Mauchly's test, and the Greenhouse-Geisser's correction on degrees of freedom was applied when necessary. In cases where interaction between time and condition was detected, the simple effects were investigated, and Bonferroni's correction was used. In the absence of interaction, the main effects of the 2 factors (time and condition) on the dependent variables were investigated. All statistical significances were tested at a = 0.05.

RESULTS

No significant interaction effect was found between condition and time for contact time ($F_{(2, 60)} = 0.483$, $p > 0.05$). A significant main effect was found for condition ($F_{(2, 60)} = 10.295$, $p < 0.001$, $\eta^2 = 0.255$, power = 0.983); post hoc comparisons indicated statistically significant greater contact time of the NS compare to the other two conditions ($F_{(1, 30)} = 1.100$, $p > 0.05$; table 1).

A statistically significant time by condition interaction ($F_{(2, 60)} = 6.781$, $p < 0.005$, $\eta^2 = 0.184$, power = 0.906) was found in flight time. The post hoc analysis showed a significant increase in flight time after PNF (mean difference = 5.386 s, p < 0.005, 95% CI = -0.009-0.002 s) and DS (mean difference = 8.015 s, p < 0.001, 95% CI = -0.012-0.005 s) (table 1).

A significant interaction effect was found between condition and time for step rate ($F_{(2, 60)} = 6.063$, $p < 0.005$, $\eta^2 = 0.168$, power = 0.870), with the post hoc analysis indicating a significant decrease in step rate after PNF stretching (Mean difference = -1.921 Hz, p < 0.005, 95% CI = 0.020 – 0.106 Hz) and after DS Mean difference = -3.273 Hz, p < 0.001, 95% CI = 0.050 – 0.161 Hz) (table 2).

The interaction effect between condition and time was significant for step length ($F_{(2,60)} = 6.631$, $p <.005$, $\eta^2 = 0.181$, power = 0.899), with the post hoc analysis indicating a significant increase in step length after PNF stretching (Mean difference = 1.950 m, p <0.005, 95% CI = -0.045 - -0.008 m) and after DS (Mean difference = 3.159 m, p < 0.001, 95% CI = -0.065 - -0.023 m) (table 2).

Furthermore, a significant interaction effect between condition and time was found for **Δy** ($F_{(2, 60)} = 6.748$, $p < 0.005$, $\eta^2 = 0.184$, power = 0.904), with post hoc analysis indicating a significant increase in **Δy** after PNF (mean difference = .0019 m, p < 0.01, 95% CI = -0.003-0.001 meters) and DS (mean difference = .0031 m, p < 0.001, 95% CI = -0.005-0.002 meters) (table 3).

The interaction effect between condition and time was statistically insignificant for **ΔL** ($F_{(2, 60)} = 2.267$, $p > 0.05$, $\eta^2 = 0.070$, power = 0.414). A significant main effect was found for condition ($F_{(2, 60)} = 13.680$, $p < 0.001$, $\eta^2 = 0.313$, power = 0.997); post hoc comparisons indicated statistically significant increase in **ΔL** after PNF and DS conditions. Further, a significant main effect was found for time ($F_{(1, 30)} = 5.151$, $p < 0.05$, $\eta^2 = 0.147$, power = 0.593) (table 3).

No significant interaction effect was found between condition and time for leg stiffness ($F_{(2, 60)} = 0.015$, $p > 0.05$). A significant main effect was found for condition ($F_{(2, 60)} = 8.520$, $p < 0.001$, $\eta^2 =$

0.221, power = 0.942); post hoc comparisons indicated statistically significant differences between PNF and Control condition (table 4) due to the greater values of the NS condition.

Further, no significant main effect was found for time ($F_{(1, 30)} = 1.100$, $p > 0.05$). The interaction effect between condition and time was statistically significant for vertical stiffness ($F_{(2, 60)} = 3.919$, $p < 0.025$, $\eta^2 = 0.116$, power = 0.685), with post hoc analysis indicating a significant decrease in vertical stiffness after PNF (mean difference = 0.667 ($kN \cdot m^{-1}$), $p < 0.05$, 95% CI = 0.071-1.263 ($kN \cdot m^{-1}$) and DS (mean difference = 1.209 ($kN \cdot m^{-1}$), $p < 0.05$, 95% CI = 0.378-2.041 ($kN \cdot m^{-1}$) (table 4).

A significant interaction effect between condition and time for $\mathbf{F_{max}}$ was revealed ($F_{(2, 60)} = 5.233$, $p < .005$, $\eta^2 = 0.149$, power = 0.813), with post hoc analysis indicating a significant increase in $\mathbf{F_{max}}$ after PNF (mean difference = 1.543 kN, $p < 0.05$, 95% CI = -0.038-0.003 kN) and DS (mean difference = 2.533 kN, $p < 0.001$, 95% CI = -0.051-0.017 kN) (table 4).

Table 1
*Mean values, SD, and percentage difference for temporal and spatiotemporal variables between pre- and post-measurement for the three conditions. **

	Tc (ms)	tf (s)
PNF		
Pre	0.202 ± 0.01	0.103 ± 0.02
Post	0.202 ± 0.01	0.109 ± 0.02 †
Δ%	0.19	5.38
DS		
Pre	0.206 ± 0.01	0.105 ± 0.02
Post	0.207 ± 0.01	0.113 ± 0.02 †
Δ%	0.67	8.01
NS		
Pre	0.207 ± 0.01	0.111 ± 0.02
Post	0.207 ± 0.01	0.111 ± 0.02
Δ%	0.23	0.34

*tc = contact time; tf = flight time; PNF = Proprioceptive Neuromuscular Facilitation; DS = dynamic stretching; NS = no stretching. †Significant difference between pre-measurement and post-measurement (p < 0.05).

Table 2
*Mean values, SD, and percentage difference for temporal and spatiotemporal variables between pre- and post-measurement for the three conditions. **

	SR (Hz)	SL (m)
PNF		
Pre	3.283 ± 0.23	1.358 ± 0.09
Post	3.220 ± 0.22 †	1.385 ± 0.09 †
Δ%	-1.92	1.95
DS		
Pre	3.227 ± 0.23	1.383 ± 0.09
Post	3.121 ± 0.17 †	1.420 ± 0.07 †
Δ%	-3.27	3.16
NS		
Pre	3.150 ± 0.19	1.414 ± 0.08
Post	3.141 ± 0.18	1.418 ± 0.08
Δ%	-0.29	0.27

SR = step rate; SL = step length; PNF = Proprioceptive Neuromuscular Facilitation; DS = dynamic stretching; NS = no stretching. †Significant difference between pre measurement and post measurement (p < 0.05).

Table 3

*Mean values, SD, and percentage difference for stiffness, kinetic, and kinematic variables between pre measurement and post measurement for the conditions. **

	ΔL (m)		Δy (m)	
PNF				
Pre	0.171	± 0.02	0.0465	± 0.01
Post	0.173	± 0.02†	0.0484	± 0.01 †
Δ%		1.36		4.01
DS				
Pre	0.177	± 0.01	0.0481	± 0.01
Post	0.183	± 0.01†	0.0512	± 0.01 †
Δ%		2.88		6.43
NS				
Pre	0.181	± 0.01	0.0504	± 0.01
Post	0.182	± 0.01	0.0506	± 0.01
Δ%		0.53		0.46

*ΔL = change in leg length; Δy = vertical displacement of the center of mass; PNF = Proprioceptive Neuromuscular Facilitation; DS = dynamic stretching; NS = no stretching

Table 4

*Mean values, SD, and percentage difference for stiffness, and kinetic, variables between pre measurement and post measurement for the conditions. **

	Kleg (km.m -1)		Kvert (km.m-1)	Fmax	
PNF					
Pre	7.91	± 1.63	29.094 ± 4.47	1.336	± 0.19
Post	7.90	± 1.47	28.427 ± 4.13†	1.356	± 0.17†
Δ%		-0.07	-2.29		0.11
DS					
Pre	7.56	± 1.13	28.084 ± 4.25	1.333	± 0.18
Post	7.51	± 1.34	27.016 ± 3.34	1.357	± 0.17
Δ%		-0.27	-0.53		2.53
NS					
Pre	7.53	± 1.25	27.162 ± 3.60	1.356	± 0.17
Post	7.51	± 1.34	27.016 ± 3.34	1.357	± 0.17
Δ%		-0.27	-0.53		2.53

* PNF = Proprioceptive Neuromuscular Facilitation; DS = dynamic stretching; NS = no stretching. Kleg = leg stiffness; Kvert = vertical stiffness; Fmax = maximal ground reaction force; †Significant difference between pre measurement and post measurement ($p < 0.05$

DISCUSSION

The purpose of this study was to examine the acute effect of DS and PNF stretching on leg (K_{leg}) and vertical stiffness (K_{vert}) and in kinematic and kinetic variables during submaximal treadmill running on female gymnasts. The comparison of DS and PNF stretching protocols revealed no significant influence of stretching type on K_{leg} and K_{vert}. However, significant percentage differences (Δ%) were found in F_{max}, Dy, flight time (t_f), step rate (SR), and step length (SL) after DS (1.54; 6.43; 8.01; -3.27; and 3.16, respectively) and PNF stretching protocol (0.11; 4.01; 5.38; -1.92; and 1.95, respectively), indicating that DS produced greater changes compared to PNF protocol.

The results of the study are consistent with findings from a previous study (Pappas et al., 2017) which revealed that DS did not influence leg or vertical stiffness during treadmill running on male physical education student. DS seems to result in a small increase in lower limb force production which may have an impact on running mechanics, even though it has been proposed that DS reduces MTU stiffness after four 30-second bouts of DS (Herda et al., 2013). It is possible that the persistence of the stiffness is due to an internal mechanism of the lower limbs that tends to keep the level of stiffness unchanged (Pappas et al., 2017).

The reduction in MTS stiffness, referred to in a previous study (Herda et al, 2013), may be due to the greater number of repetitions (4-5) that they applied. It should be noted that despite the beneficial effect of stretching on the kinetic and kinematics variables, there was no improvement in regards to the stiffness of the lower limbs. Possible explanations for DS effectiveness may be attributed to the mechanisms resulting from an increase in temperature within the muscles such as a reduction in joint and muscle stiffness, greater nerve impulse conduction rate, force velocity relationship alterations, and increased glycogenolysis, glycolysis, and high energy phosphate breakdown (McMillian et al., 2006).

It is mentioned that both protocols (DS, PNF stretching) used in the present study produce an improvement in the spring mass characteristics (F_{max}, ΔL, Δy). The increase in F_{max} after DS may be attributed to physiological factors associated with a more active warm-up (Fletcher, 2010). The longer flight time and the greater Δy that are present in both protocols are the result of the larger F_{max} and the unchanged contact time. It is noteworthy that the lower limb compression during the stance phase did not change significantly after DS and PNF stretching. Therefore, the increased F_{max} may be the result of more efficient energy storage and return or a more efficient motor unit force production. The elevated F_{max} resulted in a longer step length and consequently a lower step rate during running.

Our results reinforce findings of Pappas et al. (2017) who examined the effects of DS stretching on stiffness during running on male participants and found percentage differences (Δ%) in F_{max}, Dy, t_f, SR, and SL were 1.74, 4.50, 5.84, -2.12, and 2.25 values that are comparable with our results. The observed production of greater force from the lower extremities at the same contact time after the DS led to a longer flight time and an increased vertical displacement of the CoG on contact that may allow for more efficient storage and reuse of the elastic energy and may also have done more mechanical work at the same degree of compression (Pappas et al., 2017). Producing greater force from the lower extremities at the same contact time, following DS, led to a longer flight time and increased vertical displacement of the CoG upon contact. Therefore, it is possible that the lower limbs showed more efficient storage and reuse of the elastic energy after the DS, and also generated more mechanical work at the same degree of compression. This more efficient post DS performance improved the length and stride frequency (Pappas et al., 2017).

No other studies examined the acute effect of PNF stretching on stiffness during running; therefore, direct comparison is not possible. Data of Marek et al. (2005) suggest that both PNF stretchings reduce the force- and power-producing capabilities of the leg extensors during voluntary maximal concentric isokinetic muscle actions at 60 and $300^{o} \cdot s^{-1}$. This reduction may be due to the duration of isometric contraction and the resulting fatigue of the TM during the stretching regime, but also the duration of the stretching protocols ranging from 15 (Konrad et al., 2017; Young and Elliot, 2001) or 20 to 30 s (Barroso et al., 2012; Bradley et al., 2007; Marek et al., 2005; Sa et al., 2016). The differing effect for PNF stretching on kinetic and kinematic variables during treadmill running suggests that a neurological facilitation might be present from the preceding contraction of the TM used in the hold-relax method (Young and Elliott, 2001). In contrast to the traditional view that muscles are subject to relaxation after a twitch, other researchers claim that a lingering discharge (facilitation) results from the contraction phase of the PNF stretch (Moore and Hutton, 1980). The findings of the present study have practical applications. Although neither DS nor PNF stretching influence leg or vertical stiffness during submaximal running, both forms of stretching cause changes in kinematic parameters associated with step rate (SR), step length (SL) and lower limb's force production which in turn positively affect the running speed.

REFERENCES

Arampatzis, A., Schade, F., Walsh, M. and Brϋggemann, G.P. (2001). Influence of leg stiffness and its effect on myodynamic jumping performance. Journal of Electromyography and Kinesiology, 11 (5), 355–364.

Barroso, R., Tricoli, V., dos Santos Gil, S., Ugrinowitsch, C, and Roschel, H. (2012). Maximal strength, number of repetitions, and total volume are differently affected by static-, ballistic-, and proprioceptive neuromuscular facilitation stretching. Journal of Strength and Conditioning Research, 26(9), 2432–2437.

Belli, A. and Bosco C. (1992). Influence of stretch-shortening cycle on mechanical behaviour of triceps surae during hopping. Acta Physiologica Scandinavica, 144 (4), 401–408.

Blickhan, R. (1989). The spring-mass model for running and hopping. Journal of Biomechanics, 22, 1217–1227.

Bradley, P.S., Olsen, P.D. Portas, M.D. (2007). The effect of static, ballistic, and proprioceptive neuromuscular facilitation stretching on vertical jump performance. Journal of Strength and Conditioning Research, 21(1), 223-226.

Costa, P.B., Herda, T.J., Herda, A.A. Cramer, J.T. (2014). Effects of dynamic stretching on strength, muscle imbalance, and muscle activation. Medicine and Science in Sports and Exercise, 46 (3), 586–593.

Dallas, G., Tsiganos, G., Tsolakis, Ch., Tsopani, D., Di Cagno, A. Smirniotou, A. (2014). The acute effect of different stretching methods on flexibility and jumping performance in competitive artistic gymnasts. Journal of Sport Medicine and Physical Fittness, 54(6), 683-690.

Etnyre, B.R. and Abraham, L.D. (1986). H-reflex changes during static stretching and two variations of proprioceptive neuromuscular facilitation techniques. Electroencephalography and Clinical Neurophysiology, 63(2), 174-179.

Fletcher, I.M. (2010). The effect of different dynamic stretch velocities on jump performance. European Journal of Applied Physiology, 109 (3), 491–498.

Funk, D.C., Swank, A.M., Mikla, B.M., Fagan, T.O. and Farr B.K. (2003). Impact of prior exercise on hamstring flexibility: a comparison of proprioceptive neuromuscular facilitation and static stretching. Journal of Strength and Conditioning Research, 17 (3), 489-492.

Hardy, L. and Jones, D. (1986). Dynamic flexibility and proprioceptive neuromuscular facilitation. Research Quarterly for Exercise and Sport, 57, 150–153.

Herda, T.J., Herda, N.D., Costa, P.B., Walter-Herda, A.A., Valdez, A.M. and Crammer, J.T. (2013). The effects of dynamic stretching on the passive properties of the muscle-tendon unit. Journal of Sport Science, 31(5), 479-487.

Hindle, K., Whitcomb, T., Briggs, W. and Hong, J. (2012). Proprioceptive neuromuscular facilitation (PNF): Its mechanisms and effects on range of motion and muscular function. Journal of Human Kinetic, 31, 105-113.

Holcomb, W.R. (2000). Improved stretching with proprioceptive neuromuscular facilitation. National Strength and Condition Association, 22(1), 59-61.

Kay, A.D., Husbands-Beasley, J. and Blazevich, A.J. (2015). Effects of Contract-Relax, Static Stretching, and Isometric Contractions on Muscle-Tendon Mechanics. Medicine and Science in Sport and Exercise, 47(10), 2181-2190.

Konrad, A., Stafilidis, S. and Tilp, M. (2017). Effects of acute static, ballistic, and PNF stretching exercise on the muscle and tendon tissue properties. Scandinavian Journal of Medicine and Science in Sport, 27 (10), 1070 – 1080.

Leblebici, H., Yarar, H., Aydın, E.M., Zorlu, Z., Ertaş, U. and Kıngır, M.E. (2017). The Acute Effects of Different Stretching on Dynamic Balance Performance. *Int J Sports Stud*, 7 (3), 153-159.

Lucas, S. and Koslow, R. Comparative study of static, dynamic, and proprioceptive neuromuscular facilitation stretching techniques on flexibility. Perceptual and Motor Skills, 58 (2), 615–618.

Manoel, M.E., Harris-Love, M.O., Danoff, J.V. and Miller, T.A. (2008). Acute effects of static, dynamic, and proprioceptive neuromuscular facilitation stretching on muscle power in women. Journal of Strength and Conditioning Research, 22 (5), 1528-1534.

Marek, S.M., Cramer, J.T., Fincher, A.L., Massey, L.L., Dangelmaier, S.M., Purkayastha, S., et al. (2005). Acute Effects of Static and Proprioceptive Neuromuscular Facilitation Stretching on Muscle Strength and Power Output. Journal of Athletic Training, 40 (2), 94–103.

McMillian, D.J., Moore, J.H., Hatler, B.S. Taylor, D.C. (2006). Dynamic vs. static-stretching warm up: The effect on power and agility performance. Journal of Strength and Conditioning Research, 20 (3), 492–499.

Moore, M.A. and Hutton, R.S. (1980). Electromyographic investigation of muscle stretching techniques. Medicine and Science in Sport and Exercise, 12 (5), 322-329.

Morin, J.B., Dalleau, G., Kyrolainen, H., Jeannin, T. and Belli, A. (2005). A simple method for measuring stiffness during running. Journal of Applied Biomechanics, 21 (2), 167–180.

Pappas, P., Paradisis, G.P., Exell, T.A., Smirniotou, A., Tsolakis, C. and Arampatzis, A. (2017). Acute effects of stretching on leg and vertical stiffness during treadmill running. Journal of Strength and Conditioning Research, 31(12), 3417-3424.

Paradisis, G.P. and Cooke, C.B. (2001). Kinematic and postural characteristics of sprint running on sloping surfaces. Journal of Sport Science, 19 (2), 149–159.

Rees, S.S., Murphy, A.J., Watsford, M.L., McLachlan, K.A. and Coutts, A.J. (2007). Effects of Proprioceptive Neuromuscular Facilitation stretching on stiffness and force-producing characteristics of the ankle in active women. Journal of Strength and Conditioning Research, 21(2), 572-577.

Sa, M.A., Matta, T.T., Carneiro, S.P., Araujo, C.O., Novaes, J.S. and Oliveira, L.F. (2016). Acute effects of different methods of stretching and specific warm-ups on muscle architecture and strength performance. Journal of Strength and Conditioning Research, 30(8), 2324-2329.

Sharman, M.J., Cresswell, A.G. and Riek, S. (2006). Proprioceptive neuromuscular facilitation stretching: mechanisms and clinical implications. Sports Medicine, 36(11), 929-939.

Svantesson, U., Ernstoff, B., Bergh, P. and Grimby, G. (1991). Use of a Kin-Com dynamometer to study the stretch-shortening cycle during plantar flexion. European Journal of Applied Physiology, 62 (6), 415-419.

Woods, K., Bishop, P. and Jones, E. (2007). Warm-up and stretching in the prevention of muscular injury. Sports Medicine, 37(12), 1089-1099.

Zourdos, M.C., Wilson, J.M., Sommer, B.A., Lee, S.R., Park, Y.M. and Henning, P.C. (2012). Effects of dynamic stretching on energy cost and running endurance performance in trained male runners. Journal of Strength and Conditioning Research, 26 (2), 335–341.

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