ACUTE EFFECTS OF STRETCHING ON LEG AND VERTICAL STIFFNESS DURING TREADMILL RUNNING

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ABSTRACT

The implementation of static (SS) and dynamic (DS) stretching during warm-up routines produces significant changes in biological and functional properties of the human musculoskeletal system. These properties could affect the leg and vertical stiffness characteristics that are considered important factors for the success of athletic activities. The aim of this study was to investigate the influence of SS and DS on selected kinematic variables, and leg and vertical stiffness during treadmill running. Fourteen males (age: 22.58 ± 1.05 years, height: 1.77 ± 0.05 m, body mass: 72.74 ± 10.04 kg) performed 30-s running bouts at 4.44 $m \cdot s^{-1}$, under three different stretching conditions (SS, DS, and no stretching). The total duration in each stretching condition was 6 min and each of the four muscle groups was stretched for 40 s. Leg and vertical stiffness values were calculated using the "sine-wave" method, with no significant differences in stiffness found between stretching conditions. After DS, vertical ground reaction force increased by 1.7% ($p < 0.05$), which resulted in significant ($p < 0.05$) increases in flight time (5.8%), step length (2.2%), and vertical displacement of the center of mass (4.5%) and a decrease in step rate (2.2%). Practical durations of SS and DS stretching did not influence leg or vertical stiffness during treadmill running. However, DS appears to result in a small increase in lower-limb force production which may influence running mechanics.

Keywords: warm-up activities, kinematic, kinetic, sine-wave method, gait, physical preparation

INTRODUCTION

The purposes of the warm-up before sporting activities are to physically and mentally prepare athletes and reduce the risk of injury during subsequent performance (7). Warm-up routines commonly include submaximal aerobic activities, stretching, and a rehearsal of movement patterns that will be performed in the sport (7). Different types of stretching may be included in the warm-up, with the two main types being static stretching (SS) and dynamic stretching (DS). The positive effects of stretching on flexibility are well documented (32,47); however, the effect of stretching on subsequent performance is not clear. Numerous studies have investigated the effects of stretching on performance in athletic events (15,35,47,48,50,53,57). However, there is no clear consensus on how stretching influences performance, with SS reported to both improve (35) and reduce (47,48) performance. Similar disparity exists in the literature regarding DS, with different studies indicating that it could both positively (19,35,57) and negatively (12,26) impact on performance.

Despite the lack of agreement in the literature regarding the best form of stretching, it is widely accepted that both SS and DS alter the musculotendinous system (MTS), therefore, altering stretch-shortening cycle (SSC) performance. During SSC activities, the MTS of runners' lower limb muscles stretch and recoil, acting like a spring. When stretching is performed, elastic energy is stored in the elastic components of the MTS and then released during recoil (9,38). It has been shown that an optimum level of musculotendinous stiffness exists to maximize the use of the stored elastic energy (8) during the SSC. Following stretching, the decreased stiffness of the MTS can result in less efficient storage and reuse of elastic energy (56). It has been suggested that SS may alter the stiffness of the musculotendinous unit (MTU) (2) and increase the discharge of stored elastic energy, leading to decreased muscle activation (48) and rate of force development (13). Furthermore, a dose-dependent response to stretching has been previously indicated, with longer SS duration having a greater effect on changes in MTU properties (31). While DS has been found to alter MTU properties (26,51), it has also been linked with performance enhancement through increased metabolic factors such as heart rate, core temperature and blood flow (18). However, the authors are not aware of any research that has investigated the influence of DS duration on MTU changes.

Considering the effects of stretching on running performance, studies have shown that during endurance running activities (36), a stiffer MTU is more effective than a compliant MTU and can contribute to performance improvements (25). This notion has been reinforced by the positive relationship reported between inflexibility and running economy (28,30). However, studies investigating the effects of SS on submaximal running events are inconclusive and have reported improved (22), unaffected (1,23,39,42), and decreased running economy (55). A positive correlation between leg stiffness and running economy has been widely evidenced (3,5,14,21,25). However, previous studies have indicated no positive influence of DS on running performance at a moderate (58) or high running pace (19,35,47).

The spring mass model (SMM) is widely used to describe lower extremity stiffness (9,38). In running, leg stiffness is defined as the ratio of peak vertical ground reaction force to peak leg compression during stance, whilst vertical stiffness is the ratio of peak vertical force to vertical displacement of the mass center during stance (16). Leg and vertical stiffness can be affected by the functional properties of the MTS, which may be influenced by stretching. Furthermore, the energy exchange between muscles, tendons, and ligaments can be influenced by the leg and vertical stiffness during running (4,10), impacting on performance.

Leg stiffness may be used to represent the mechanical function of the lower limbs and changes in this variable may affect performance at moderate running speeds during endurance running. Although stiffness is considered an important factor in running performance (4,14,16), the acute effects of different stretching methods during training and competition on vertical and leg stiffness are unknown. To the authors' knowledge, only one previous study (27) has examined the influence of SS on leg stiffness, concluding that SS did not significantly affect leg stiffness.

Based on the previously reported links between stiffness and performance and the influence that stretching may have on stiffness, if a specific warm-up protocol greater influences stiffness, it could positively or negatively influence performance. While both SS and DS decrease MTU stiffness, the influence of both stretching types on lower limb stiffness and running kinematics and kinetics that may influence performance is not well understood.

Therefore, the aim of this study was to investigate the influence of SS and DS on leg and vertical stiffness, kinematic and kinetic variables during submaximal treadmill running. The purpose of the study was to inform future warm up protocols and physical preparation as to whether there are benefits to SS or DS. It was hypothesized that both SS and DS would acutely change the leg and vertical stiffness during treadmill running.

METHODS

Experimental Approach to the Problem

To test the hypothesis of this study, the effects of two stretching protocols and a control condition (no stretching [NS]) on leg and vertical stiffness and on the related kinetic and kinematic parameters were investigated. The applied stretching conditions (SS, DS, and NS) were chosen on the basis of previous research (47). A withinsubject experimental design was used with all the participants completing the SS, DS, and NS protocols randomly. Pre-stretching and post-stretching tests were used to evaluate the effects of stretching on the selected dependent variables. Participants attended three familiarization sessions; on the first day, the participants undertook a preliminary session where they successfully performed five to seven 30-s runs on the treadmill (Technogym 1200, Italy) at 4.44 $m \cdot s^{-1}$. After 15 min of recovery, they performed a 1-min run at 5.55 $m \cdot s^{-1}$ to ensure that the speed of 4.44 $m \cdot s^{-1}$ corresponded to a submaximal intensity. On the second day, participants were familiarized with the testing protocols, and on the last day, participant characteristics and lower limb length (great trochanter to ground whilst standing) was collected. All testing procedures took place in the fall and during the athletes' usual practice time of day, which was between 4 and 8 o'clock pm. Participants were asked to wear the same shoes and clothing during all trials, and to consume only a light meal at least 4 h before testing. During the testing period, the participants were asked not to undertake any other sport activity and to control their diet. The training facilities were well lit and kept under stable environmental conditions (i.e., temperature 25° C and humidity 52%).

Subjects

Fourteen male physical education students participated in this study ([Mean ± SD] age: 22.58 ± 1.05 years, height: 1.77 ± 0.05 m, body mass: 72.74 ± 10.04 kg). No participants had any lower limb injury in the previous 6 months, all had experience in treadmill running and none of them had any lower limb length asymmetry. To verify the sample size of this study, a statistical power calculation was performed (6). The sample size was adequate for the variables with significant interactions or main effects ($\alpha \leq 0.05$ for Type I error), whereas it was not adequate for the variables with no significant interactions or main effects ($\beta \leq 0.2$ for type II error). This is considered a research limitation. 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 provided written informed consent prior to commencement of the study.

Procedures

Stretching Protocols

SS: The four muscle groups stretched were the quadriceps, hamstrings, hip extensors, and plantar flexors. ***Quadriceps*****:** Participants lay on their right side and leaned on the right forearm for balance. They then flexed the left knee, grasped the left ankle, and pulled the ankle up toward their buttocks until a slight stretch was felt in the quadriceps. ***Hamstrings:*** The participants lay on the back with both legs extended. They flexed the left hip while keeping the knee extended, and brought the thigh toward the chest with hands placed on the posterior thigh. They pulled the thigh toward their chest until a slight stretch was felt in the hamstrings. ***Hip extensors:*** The participants lay on the back with both legs extended. They flexed the left knee and hip and brought the thigh toward the chest with hands placed on the posterior thigh. They then pulled the thigh toward their chest until a slight stretch was felt in the hip extensors. ***Plantar flexors:*** The participants stood and placed their hands on the wall. The leg that was not being stretched was placed 15 cm away from the wall, and the one being stretched was 50 cm away from the wall. They then leaned forward and slightly flexed the front knee. At the same time, they extended the rear knee while keeping that heel in contact with the floor until they felt a slight stretch in the calf of the rear leg. They stretched the target muscles of the left leg for 20 sec, and the same procedure was repeated for the right leg. All stretches were performed twice, with a resting period of 15 s between each muscle stretching (total stretching time 6 min).

DS: The participants performing DS contracted the antagonist of the target muscles intentionally in an upright standing position and flexed or extended the relevant joints once every 2 s for each leg alternatively. This stretching was performed for 80 s. The next muscle group was flexed after a resting period of 15 s. The sequence of the stretched target muscle and the resting periods in SS and DS were identical (total stretching time 6 min). ***Quadriceps:*** The participants contracted their hamstrings intentionally and flexed the knee joint so that the heel touched their buttocks. ***Hamstrings:*** The participants contracted the hip flexors intentionally with the knee extended and flexed their hip joint so that the leg swung up to the anterior aspect of the body. ***Hip extensors:*** The participants contracted hip flexors intentionally with the knee fixed and flexed their hip joint so that the thigh came up toward the chest. ***Plantar flexors:*** Initially, the participants raised one foot and fully extended the knee. Then, they contracted their dorsiflexors intentionally and dorsiflexed the ankle joint so that the toes were pointing upward. NS: The participants sat for 6 min and did not perform any stretching.

Data Collection

During data collection, participants performed a 5-min warm-up running on the treadmill at 2.22 $m \cdot s^{-1}$, followed by the pretests. They randomly performed one of the three stretching exercises (SS, DS, and NS), followed by posttests. There was an interval of 48 h between the testing days. During the pretests and posttests, they performed 30-s 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 a previous study (40).

To calculate vertical and leg stiffness, 10 consecutive steps were recorded, starting from the third second of each 30-s running bout. Flight and contact time were measured using a Casio EX-F1 (Tokyo, Japan) high-speed video camera, which was placed 1 m behind the treadmill, perpendicular to the frontal plane, at a height of 40 cm (43). The frame rate was selected at 300 Hz, and the shutter speed at 1/1250; the zoom was adjusted to obtain a limited area of shoe-treadmill contact (field of view 40 × 30 cm).

Data Analysis

The Quintic Biomechanics v21 (Sutton, UK) software was used for the analysis of all video-recorded steps, with all trials analyzed by the same person. Contact and flight times were obtained according to regular procedures (34), with a total of 10 consecutive steps of each leg that were video analyzed. The measured values of flight and contact time of the 10 consecutive steps were averaged, and the mean values were used for calculating leg and vertical stiffness. Mean values were also used for estimating step rate and step length, according to Paradisis and Cooke (46).

Morin et al. (40) proposed the “sine wave” method to measure leg and vertical stiffness in running by using body mass, forward velocity, lower limb length, flight time, and contact time. This method assumed that the force profile during contact can be represented by a simple sine function and was demonstrated to produce lower bias (0.12–6%) than the reference values from the force plate (40). Coleman, Cannavan, Horne, and Blazevich (11) compared several mathematical models and concluded that the sine wave method provided values closest to those provided by the gold standard model (5% mean difference; ICC = 0.901), suggesting that the sine wave method is the most appropriate method despite its simplicity. Additionally, the authors proposed a correction factor (1.0496 K) that could improve the accuracy of the method.

The 10-step average value for the contact and flight times was used for estimating the vertical and leg stiffness according to the sine-wave method equations:

$$K_{vert} = \frac{F_{max}}{\Delta y} \quad (1)$$

$$F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c} + 1\right) \quad (2)$$

$$\Delta y = -\frac{F_{max}{t_c}^2}{m\pi^2} + g\frac{{t_c}^2}{8} \quad (3)$$

$$K_{leg} = \frac{F_{max}}{\Delta L} \quad (4)$$

$$\Delta L = L - \sqrt{L^2 - \left(\frac{vt_c}{2}\right)^2} + \Delta y \quad (5)$$

K_{vert} is the vertical stiffness; K_{leg}, the leg stiffness; F_{max}, the maximal ground reaction force during contact; Δy, 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. Before further analysis, leg and vertical stiffness values were corrected with the correction factor of 1.0496 K (11), by multiplying calculated values by this factor.

Reliability

Intra-analyzer reliability was obtained by repeating the analysis for 10 consecutive steps of the same participant. The analysis procedure mentioned above was repeated three times by the same digitizer, with a 1-week interval between each. The intra-class correlation coefficient [ICC] was found to be 0.999). The reliability of participants' analyzed parameters during treadmill running was determined in a previous study (44). Three 30-s running bouts with 2-min inter-bout rest were performed to examine the intra-day reliability. To examine the inter-day reliability, 30-s single running bouts were performed on three separate days with 24–48-h inter-bout intervals. The reliability statistics included ICC, standard error of the mean, and minimum difference (MD) (54). All analyzed parameters produced high reliability (Table 1).

*** TABLE 1 NEAR HERE ***

Statistical Analyses

The IBM Statistical Package for the Social Science (SPSS) (version 21) was used for the statistical analysis. The arithmetic mean, standard deviation, 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 (SS, DS, and NS) on the dependent variables, a two-way (time x condition) repeated measures ANOVA was used for the statistical analysis. 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 Bonferonni's correction was used. In the absence of interaction, the main effects of the two factors (time and condition) on the dependent variables were investigated. All statistical significances were tested at $\alpha = 0.05$.

RESULTS

The statistical analyses revealed that the interaction effect between time and condition was statistically insignificant for leg stiffness ($F_{(2, 26)} = 0.228$, $p > 0.05$). Likewise, no statistically significant main effects were found for time ($F_{(1, 13)} = 0.267$, $p > 0.05$) or condition ($F_{(2, 26)} = 0.123$, $p > 0.05$) (Table 2). Regarding vertical stiffness, the statistical analyses demonstrated no significant interaction effect between the two factors ($F_{(2, 26)} = 2.769$, $p > 0.05$) and no significant main effect for time ($F_{(1, 13)} = 2.304$, $p > 0.05$). A statistically significant main effect was found for condition ($F_{(2, 26)} = 3.681$, $p < 0.05$, $\eta^2 = 0.221$, power = 0.625); however, post hoc comparisons indicated statistically insignificant differences among the three levels (Table 2).

*** TABLE 2 NEAR HERE ***

The F_{max} results indicated a significant interaction effect between time and condition ($F_{(2, 26)} = 3.438$, $p < 0.05$, $\eta^2 = 0.209$, power = 0.593), with the post hoc analysis revealing a statistically significant increase in F_{max} after DS (Mean difference = 0.030 kN, $p < 0.05$, 95% CI = 0.000–0.060 kN) (Table 2). Additionally, a significant interaction effect was found between time and condition for Δy ($F_{(2, 26)} = 9.340$, $p < 0.05$, $\eta^2 = 0.418$, power = 0.963). The post-hoc analysis showed that Δy significantly increased after DS (Mean difference = 0.002 m, $p < 0.05$, 95% CI = 0.001–0.003 m) (Table 2). However, this study found no significant interaction effect between time and condition for ΔL ($F_{(2, 26)} = 1.120$, $p > 0.05$) and no significant main effect either for time ($F_{(1, 13)} = 1.155$, $p > 0.05$) or condition ($F_{(2, 26)} = 0.590$, $p > 0.05$) (Table 2).

Regarding flight time, the interaction effect between time and condition was statistically significant ($F_{(2, 26)} = 6.388$, $p < 0.05$, $\eta^2 = 0.329$, power = 0,864), with the post hoc analysis indicating a significant increase in flight time after DS (Mean difference = 0.007 s, $p < 0.05$, 95% CI = 0.002–0.011 s) (Table 3). A significant interaction effect was found between time and condition for step rate ($F_{(2, 26)} = 9.288$, $p < 0.05$, $\eta^2 = 0.417$, power = 0.962), with the post hoc analysis showing a significant decrease in step rate after DS (MD = 0.067 Hz, $p < 0.05$, 95% CI = 0,032–0.101 Hz) (Table 3). The interaction effect between time and condition was also statistically significant for step length ($F_{(2, 26)} = 9.869$, $p < 0.05$, $\eta^2 = 0.432$, power = 0.971), while the post hoc comparisons revealed that DS significantly increased step length (MD = 0.034 m, $p < 0.05$, 95% CI = 0.017–0.050 m) (Table 3). Finally, there was no significant interaction effect between time and condition for contact time ($F_{(2, 26)} = 0.261$, $p > 0.05$) and no significant main effect for time ($F_{(1, 13)} = 0.324$, $p > 0.05$) or condition ($F_{(2, 26)} = 0.177$, $p > 0.05$) (Table 3).

*** TABLE 3 NEAR HERE ***

DISCUSSION

The aim of this study was to investigate the influence of SS and DS on leg and vertical stiffness, kinematic and kinetic variables during treadmill running. When comparing the SS and DS protocols (total stretching duration in each protocol = 6 min, 40 s stretching per muscle group) results indicated no significant influence of stretching type on leg and vertical stiffness. In light of these results, the hypothesis that both SS and DS would acutely change the leg and vertical stiffness is rejected. Despite the similarities reported in leg and vertical stiffness values, significant changes were found in F_{max}, Δy, flight time, step rate, and step length (1.7%, 4.5%, 5.8%, −2.1%, and 2.3%, respectively) following DS. None of the analyzed variables were altered after SS implementation.

To the authors’ knowledge, no previous study has investigated the effects of stretching on stiffness during running; therefore, direct comparison is not possible. However, the only study that has examined acute effects of stretching on stiffness during two-legged hopping reported no changes after 3-min SS of the triceps surae (27). The authors of that previous study suggested that the finding may be due to intra-limb compensation strategies that regulate stiffness (27). These findings are in agreement with the present study's results, despite different stretching durations.

Results from the current study showed that neither SS nor DS altered leg or vertical stiffness even though it has been proposed that both SS and DS reduce musculotendinous stiffness (2,13,26). According to previous studies, runners were able to regulate their leg stiffness when running on surfaces with different stiffness characteristics (17) and different simulated gravity levels (24), thus maintaining an unaltered overall stiffness. These findings support the notion that individuals may use compensatory mechanisms to moderate overall leg stiffness and could explain why stretching, which has been shown to change MTU stiffness, did not alter leg stiffness. It has been shown that muscle length changed minimally during the contact phase in running animals (49). Therefore, it could be suggested that the tendons contribute more to the compliance of the MTS and have a greater influence on leg stiffness than muscle stiffness (17). Previous research has also suggested that decreased MTU stiffness after 5 repetitions of 1-min SS was the result of increased compliance of the muscular portion of the MTU, rather than changes in tendon stiffness (41). It is likely that in the present study, which included a lower stretching duration than previous studies (27,41), changes in the MTU properties following SS are the results of changes in muscle stiffness rather than tendon stiffness. Previous studies incorporating greater stretch durations have shown a lack of agreement relating to the influence of SS on tendon stiffness (31,32,33,41), with only a 10 min stretch duration altering tendon stiffness (33). Therefore, the lack of change in stiffness reported in the present study may have been due to the duration of stretches employed, which were selected based on common stretching durations performed by athletes. Regarding DS, Herda et al. (26) reported a link with decreased MTU stiffness following four 30-s bouts of DS whilst Samukawa et al. (51) showed that five 30-s bouts of DS can alter MTU properties and change tendon length, although evidence related to tendon stiffness changes was not reported. Conversely, no change in leg or vertical stiffness was reported in the current study. One possible reason for the different MTU properties reported in the present study when compared with previous investigations may be shorter stretch duration (total stretching duration = 6 min, two 20-s bouts on each muscle). Furthermore, it is possible that the previously mentioned compensatory mechanisms may be able to maintain leg stiffness despite possible alterations in MTU properties (34,37,52).

The spring mass characteristics reported in the current study (F_{max}, ΔL, Δy), remained unchanged after SS. The unaltered F_{max} during ground contact agrees with previous studies that examined the effect of stretching on SSC (23,39). However, this is contrary to the results found by Godges et al. (22), who indicated increased performance after SS. The lack of agreement between the previous (22) and current studies is possibly due to differences in stretching durations, number of muscles stretched and stretching technique. Regarding the temporal characteristics, the present study indicated no changes after SS implementation, indicating that the runners produced the same level of force during the same contact time. In addition to temporal characteristics, step length and rate remained unchanged. Hunter and Smith (29) suggested that runners adopt a self-optimized step length-rate combination to minimize energy consumption. Therefore, it appears that the SS employed in this study did not impair the participants' running patterns.

In the present study, it was found that DS led to significant increases in flight time (0.007 s, 5.8%), Δy (0.01 m, 4.5%) and F_{max} (0.03 kN, 1.7%), whereas contact time remained unchanged. The increase in F_{max} following DS may be attributed to physiological factors associated with a more active warm up (18). Another possible reason for the enhanced performance following DS may be the rehearsal of more task-specific movement patterns than SS (20). These results agree with the findings of previous studies, which indicated that DS either enhanced (19,35) or did not change running performance (47,58). The larger F_{max} and unchanged contact time following DS resulted in a longer flight time and a greater Δy. However, compression of the lower limbs during the stance phase was not significantly altered after DS. Therefore, the increased F_{max} may be the result of more effective energy store and return or more effective motor unit force production. The increased F_{max} resulted in a longer step length and subsequent lower step rate during running. During endurance running events this increase in step length and maintained leg stiffness may lead to performance improvements due to fewer steps being taken over the duration of a race.

Limitations of this study include assumptions relating to the spring-mass model, namely that a) lower limb length, at the moment of ground contact, is equal to the standing lower limb length and b) horizontal displacement of the mass center is the same before and after mid-stance. These assumptions might have introduced error into the stiffness estimations (9,38). Although, the spring mass model has been shown to successfully describe the general characteristics of locomotion (9). Furthermore, the results of the present study must be considered with caution given the limited sample size.

PRACTICAL APPLICATIONS

This study’s findings indicate that, for the durations used during warm-up activities, neither SS nor DS acutely change leg or vertical stiffness during submaximal running. However, DS does appear to enhance the force production of the lower limbs and subsequent step length during medium-speed treadmill running. This increase in step length could increase performance by potentially increasing step velocity during over-ground running at self-selected pace or by reducing the number of ground contacts that are required throughout an endurance running event. The diversity of the effects of stretching suggests that the type of stretching used should be selected on the basis of the task at hand and associated movement patterns. It is recognized that athletes become accustomed to warm-up routines and that alteration of a routine could lead to an adverse effect, as athletes might be unable to reach maximum performance. Therefore, it is suggested that DS be trialed by coaches and athletes in a training environment to investigate whether it leads to a positive influence on individual athlete's performance that could then be used in competition.

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