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Functional stretching decreases knee joint loading in male athletes with gastroc--soleus tightness

Farhad Rezazadeh^{1,*}, Seyyed Sadredin Shojaeddin¹, Georgian Badicu^{2,*}

¹Department of Biomechanics and Sport Injuries, Kharazmi University of Tehran, 15719-14911 Tehran, Iran ²Department of Physical Education and Special Motricity, Transilvania University of Brasov, 500068 Brasov, Romania

***Correspondence:** rezazade.farhad@gmail.com (Farhad Rezazadeh); georgian.badicu@unitbv.ro (Georgian Badicu)

Abstract

Background and objective: Tightness of the gastroc--soleus muscle complex is one of the limiting factors of the ankle joint's range of motion (ROM) during daily activities. The aim of this study was to investigate the effectiveness of functional and extra-functional stretching of the gastrocnemius--soleus complex on knee joint loading in athletes with limited ankle dorsiflexion.

Material and methods: In this cross-sectional study, 30 male athletes with gastrocnemius--soleus shortness were recruited and randomly divided into three equal-size groups of functional stretching, extra-functional stretching, and a control group. The extra-functional stretching group performed stretching exercises three times per day for eight weeks. The functional stretching group was instructed to change their gait pattern via increased heel strike during daily activities.

Results: None of the stretching programs reduced the knee flexion angle in heel contact (p > 0.05). The knee flexion angle was significantly increased in the stance phase in the functional group ($p \le 0.05$). Walking speed was increased significantly in the extra-functional group ($p \le 0.05$). The knee adductor moment and external rotation moment decreased significantly in the functional group ($p \le 0.05$).

Conclusion: An eight-week functional stretching program in this study led to a reduction of knee loading in the frontal and horizontal planes in comparison to the extra-functional stretching group, demonstrating the effectiveness of functional stretching in improving knee joint biomechanics during walking.

Keywords

Functional stretching exercises; Knee; Gastroc--soleus; Bomechanics

1. Introduction

Limitations in flexibility of the gastroc–soleus muscle complex are one of the limiting factors for the ankle joint's range of motion (ROM) during daily activities. Such limitations occur in response to changed or increased muscle demands, like excessive loading on the muscle during pre-season preparation phases [1], repeated microtrauma beyond the fascia tolerance in collisional sports [2], and poor posture adoption [3]. Most lower limb injuries, including anterior cruciate ligament (ACL) injury, patellar tendon injury, patellofemoral pain syndrome, Achilles tendon injury, and lack of energy absorption, are associated with limited ankle dorsiflexion (DF) ROM [3, 4].

It is believed that limited ankle DF may impair subtalar joint motion and prevent the close-packed position of the ankle joint needed during walking and running, which not only affects the stability of the ankle and knee but also impairs postural stability [4–6]. Also, calf muscle tightness leads to increased tensile force on the plantar fascia during the stance phase of gait [7].

The knee joint, as the main lower limb motor joint, is

the most vulnerable and susceptible joint. Knee impairments are common physical problems that impact the normal living ability and mental health of patients affected by them. The knee's influences mainly include supporting body weight, assisting lower limb swing, and absorbing strike shock [8].

Ankle DF ROM of less than 10 degrees prevents optimal anterior tibia advancement over the ankle so that the bodyweight cannot move over the forefoot optimally [3], which ultimately leads to changes in the gait parameters and to knee compensating patterns such as excessive knee flexion at the initial contact and knee valgus (the predictor of osteoarthritis) [9]. Moseley et al. [10] examined the effect of decreased ankle flexion ROM on the kinematics and kinetics of the ankle, knee, and hip joints. Their study revealed that decreased ankle DF during walking could be an important contributing factor for reduced hip extension ROM at the terminal stance, as well as excessive extension of the knee in the stance phase. Ota et al. [11] confirmed that limited ankle ROM, following gastroc-soleus shortness complex, affects the knee joint loading in the frontal plane, which is likely associated with increased risk of knee osteoarthritis and reduced hip muscle strength.

Considering the negative effects of gastroc-soleus complex tightness and aiming to reduce its pathological effects on the motor system, stretching exercises are primarily important and commonly prescribed by therapists [12]. ROM challenges can be either functional or extra-functional. Techniques or movement patterns that resemble the normal daily activities of the individual [13, 14] (i.e., walking with an increased heel strike in this study) are called functional challenges. ROM challenges that use movement patterns that are outside the individual's repertoire or experience are called extra-functional challenges. Sitting on the floor and forcefully pulling on the foot to stretch the calf muscle is an example of an extra-functional passive approach [13]. A standing calf muscle stretch is an example of an extra-functional active approach. According to Lederman 2014, most traditional stretching techniques fall within the extra-functional category. They include techniques such as static and dynamic stretching, proprioceptive neuromuscular facilitation (PNF), muscle energy techniques (METs), and ballistic stretching [13].

Several studies have reported positive effects of gastrocsoleus stretching programs on the ankle joint ROM [11, 15, 16]. However, based on the previous studies, one can say that in addition to the use of traditional (extra-functional) training programs, they were limited to goniometers for measuring joint ROM, and the function of the ankle joint during a functional motion pattern (walking) was ignored [11, 15, 16]. The effectiveness of stretching programs in previous research remains controversial [11, 12, 15–17], due to differences in the type of stretching program technique and evaluation tools. On the other hand, functional stretching is a new approach that utilizes movement patterns that are more familiar to patients [13, 14]. Also, a functional stretching technique involving the entire kinetic chain, done at any time or place, does not require specific tools or dedicating special time and considers the specificity principle of training [13, 14]. According to Lederman [13], functional stretching exercises that include patterns similar to daily activities, such as walking, follow the similarity and within-context principles. Functional stretching of the gastroc–soleus muscles was studied in a recently published article by Ghasemi *et al.* [14], wherein they investigated the effect of functional stretching exercises on functional outcomes in spastic stroke patients.

It seems that the gait cycle to evaluate the dynamic posture and effectiveness of a stretching program is the most appropriate tool [13, 18]. On the other hand, the type of stretching technique is another important factor for assessing stretching programs' effectiveness [13]. Previous studies showed that restricted ankle DF leads to mechanical changes of the lower extremity joints in the kinetic chain [19]. With regard to the importance of the external moment of the knee, abnormal external rotation of the knee during the stance phase is a common cause of lateral deviation of the patella in people with gastroc-soleus complex shortness, which is a known risk factor for patellofemoral pain [20]. Therefore, after identifying the underlying causes of lower extremity injuries in athletes (external knee rotation), it is necessary to emphasize those training programs focused on reducing the rotational moment. Also, studies have shown that functional stretching methods are more effective in improving gait performance [14]. Therefore, we intended to compare the effects of eight weeks of functional and extra-functional stretching programs on knee joint biomechanics.

Furthermore, any improper change in the movement system, like muscle imbalance or weakness, increases the joint forces significantly [21]. Thus, it is important to evaluate the effectiveness of joint forces from modifying gait patterns through different stretching exercises among people with gastroc-soleus muscle stiffness. We assumed that the application of both extra-functional and functional stretching programs in individuals with limited DF would result in improved kinematic parameters of the knee. Another assumption was that a functional stretching program with increased heel strike would have a greater effect on gait biomechanics than extra-functional stretching. We hypothesized that a functional stretching program would decrease knee joint loading in athletes with gastroc-soleus tightness, so this study aimed to compare the effects of functional and extra-functional stretching of the gastroc-soleus muscle on the knee joint biomechanics during gait.

2. Methods

2.1 Participants

This cross-sectional study was performed on 30 professional male runners with average age, mass, and height of 25.2 \pm 1.2 years, 76.6 \pm 4.7 kg, and 179.9 \pm 1.4 cm, respectively, and at least 5 years of sports experience. All participants had gastroc–soleus tightness (mean ankle flexion ROM in the knee extension position was 7.5 \pm 0.44 and that in the knee flexion position was 8.1 \pm 0.33 degrees). Participants were randomly assigned to three equal-size groups of functional



FIG. 1. Gastroc-soleus stretching techniques. (a) Stretching in a closed-kinetic-chain (CKC) position; (b) Stretching in an open-kinetic-chain (OKC) position with knee extended and with knee flexed.

stretching, extra-functional exercises, and control using Excel (version 2019; Microsoft Corporation, Redmond, WA).

Individuals recruited from the available community were selected using the findings of a preliminary study to determine the sample size based on the variance of the test parameters in 5 participants.

Inclusion criteria included gastroc-soleus shortness identified by toe walking and DF ROM of less than 10 degrees [3]. Exclusion criteria were a history of trauma or ankle surgery, bone pathology, neurological disorders, and rheumatoid arthritis, inflammatory diseases, or any conditional abnormalities affecting the research process, such as supinated or rigid foot [12].

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study before data collection. The study was approved by the university's institutional review board. Participants had the right to decline to participate and to withdraw from the research procedure once it had started.

2.2 ROM measurements

The DF ROM was measured using a universal goniometer in the prone position in both the knee-flexed (for soleus shortness) and extended-knee (for gastrocnemius shortness) positions. For each ROM measurement, the participant was completely relaxed, and they moved their ankle into DF from a neutral starting position (i.e., 90° angle between shank and foot segments). Five measurements were obtained randomly in each position. All ROM measurements were collected by the same investigator, and analysis of these data revealed high reliability across trials (extended-knee assessment: intraclass correlation coefficient = 0.90, standard error of measurement = 1.8° ; flexed-knee assessment: intraclass correlation coefficient = 0.84, standard error of measurement = 2.6°) [22, 23].

2.3 Gait measurements

Kinematic variables of the gait were identified using the findings of a preliminary study regarding the effect of changing gait pattern with an increased heel strike pattern in healthy participants. Pre-test and post-test measurements of kinematic variables for the dominant limb were done using a 6camera, motion-capture system (Motion Analysis MX40S., VICON, USA) with a sampling rate of 120 Hz. Ground reaction forces during walking in the pre-/post-test were measured at a 1200 Hz sampling rate using a Kistler force plate (30 \times 50, Switzerland) embedded in the middle of a 6meter walkway. A standard 9 mm marker was used for kinematic data collection. Retroreflective markers were placed on the heads of the first and fifth metatarsals, on the posterior aspect of the calcaneus, and on the medial and lateral malleoli, lateral knee joint lines, lateral epicondyle of the femur, and anterior superior iliac spines, as well as laterally on the shank

and thigh on the dominant foot; these were determined by anatomic definitions from the VICON Clinical Manager [24, 25]. The position data of markers and ground reaction forces were processed with the Vicon dynamic model using Plug-in-Gait-Workstation software version 4.3 to generate the kinematic data and joint moment for sequential analysis.

Each participant was instructed to walk barefoot along the walkway at a self-selected speed. Practice trials were permitted until the participant was comfortable with walking and was able to contact the force plate with only one foot without altering his gait. Typically, three practice trials were performed. The stance phase was determined from the moment the heel touched the force plate until toe-off leaving the force plate.

2.4 Data reduction

Moments of force (moments) during the stance phase were calculated via mathematical equations involving the inverse rigid-body dynamics method and link-segment model. To calculate the knee adduction and rotation moment during the stance phase, first, the knee moment was calculated on the frontal and horizontal planes, and then the time series data of moment-time were normalized to a percentage. The first 60% of the normalized time series was considered as the stance phase. According to ISB recommendations, the positive and negative moments were considered as the knee external rotation and adduction moments, respectively [2, 11]. Joint moments were normalized for body weight and height. Spatio-temporal parameters (stride length, cadence) were obtained by using the force platform and kinematic information to define the initial foot contact times and distance parameters. Average kinematic and kinetic values for each participant's knee joint for the pre-/post-treatment conditions were obtained from 3 trials (average of both right and left lower extremities, providing an average of 6 values for each condition). The kinematic data were smoothed using a 6 Hz Butterworth filter.

2.5 Intervention

The intervention groups performed stretching exercises 3 times per day for 8 weeks. Each participant performed an overall 12 minutes of stretching per session. The functional stretching group was instructed to change their gait pattern via increased heel strike during daily activities. The interventions were performed on both feet. extra-functional stretching program included both closedkinetic-chain (CKC) (opposing a wall, stretching with knee flexed (first position) and extended (second position)) and opened-kinetic-chain (OKC) (sitting position, with the knee extended (first position) and knee flexed (second position)) exercises (Fig. 1). Every stretching position was held for 45 seconds and was repeated on each lower extremity twice, alternating sides with each stretch. The choice of exercises in each session was completely randomized, and all stretches were carried out for both extremities [13, 16, 25].

The functional stretching group aimed to change their gait pattern via increasing step length with the knee extended

and increased heel strike in the early stance phase of gait (i.e., participants were instructed to walk with increased heel strike, leading to large ankle DF at heel contact). The idea for this stretching method came from the Lederman functional stretching approach [13] and Sharman walking exercises for movement impairment syndromes of lower extremities [26]. The control group performed their daily activities without any stretching exercises.

2.6 Statistical analysis

After determining the normal distribution of data using the Shapiro–Wilk test, statistical analysis was carried out using separate 3×2 (training group (functional stretching, extra-functional stretching, and control) \times time (pre-test vs. post-test)) repeated-measures ANOVAs. If there was a significant interaction for any dependent variables, simple main-effects analysis was performed via one-way repeated-measures ANOVAs for each factor, with pairwise comparisons identifying significant differences. Effect sizes were determined by converting partial eta-squared (η 2p) to Cohen's d. Cohen's d values of \leq 0.4, 0.5–0.7, and \geq 0.8 indicated a small, moderate, and large effect size, respectively [27]. All analyses were done using SPSS (SPSS, IBM, Armonk, NY, USA), and significance for all analyses, before any corrections, was set at $p \leq$ 0.05.

3. Results

Changes in DF for each participant based on group allocation are presented in Table 1. There were no significant differences between the groups in the baseline measures, confirming that the randomization process was successful (p > 0.05). Ankle DF ROM was increased significantly after functional and extra-functional stretching in the extended knee position ($p \le 0.05$) (Table 1).

TABLE 1. Dorsiflexion range of motion in tow position of flexed (a) and extended knee (b), measurement (mean \pm SD).

| Group | n | Pre-test | Post-test | | |
|-------|----|-----------------|--------------------|--|--|
| CG | 10 | (a) 6.1 \pm 2 | (a) 6.2 ± 1 | | |
| | | (b) 6.8 ± 1 | (b) 6.7 ± 2 | | |
| FG | 10 | (a) 5.7 \pm 1 | (a) 10 ± 1 | | |
| | | (b) 5.9 \pm 1 | (b) $11.8 \pm 2^*$ | | |
| EFG | 10 | (a) 6.2 ± 2 | (a) 10.5 ± 1 | | |
| | | (b) 5.8 ± 2 | (b) $10.8 \pm 3^*$ | | |

CG, Control group; FG, Functional stretching; EFG, Extrafunctional stretching. *Significant difference.

The means (standard deviations) for kinetic and kinematic parameters of the knee joint during the stance phase of gait in the experimental groups are also presented in Table 1.

The statistical analyses indicated significant time × group interaction for stride length (p < 0.001, d = 1.95); pairwise comparison revealed increased stride length after functional and extra-functional stretching (p = 0.006 and p = 0.001, respectively) (Table 2). Also, we found significant time × group interaction for cadence (p < 0.001, d = 1.77);

| Variable | Group | Pre-test | Post-test | p (Cohen's d) | Main effect: | Main effect: | Interaction: |
|---|-------|---------------|---------------|---------------|-------------------|-----------------------|--------------------------|
| | | | | | Group (Cohen's d) | Time (Cohen's d) | Time × Group (Cohen's d) |
| | FG | 1.21 (0.09) | 1.34 (0.06) | 0.006* | 0.05 (0.994) | <i>p</i> < 001 (2.23) | p < 0.001 (1.95) |
| Stride length (m) | EFG | 1.26 (0.08) | 1.55 (0.19) | 0.001* | | | |
| | CG | 1.27 (0.09) | 1.28 (0.12) | 0.55 | | | |
| | FG | 1.06 (0.15) | 1.13 (0.10) | 0.09 | 0.04 (1.03) | 0.002 (1.33) | p < 0.001 (1.77) |
| Cadence (steps/min) | EFG | 1.16 (0.16) | 1.53 (0.32) | 0.005* | | | |
| | CG | 1.19 (0.14) | 1.14 (0.11) | 0.1 | | | |
| Varian antancian DOM | FG | 27.31 (20.9) | 34.9 (4.03) | 0.03* | | | |
| Knee nexion-extension ROW | EFG | 32.8 (120.7) | 35.3 (20.6) | 0.31 | 0.21 (0.692) | 0.001 (1.39) | 0.013 (1.22) |
| during stance phase (degrees) | CG | 19.61 (110.1) | 21.75 (18.3) | 0.42 | | | |
| | FG | 8.11 (3.3) | 11.71 (4.4) | 0.5 | | | |
| Knee nexion angle at initial | EFG | 14.20 (6.4) | 10.2 (4.3) | 0.5 | 0.38 (0.505) | 0.42 (0.314) | 0.51 (0.448) |
| contact (degrees) | CG | 9.04 (5.2) | 10.17 (4.1) | 0.68 | | | |
| V I I I I I I I I I I I I I I I I I I I | FG | -202 (0.62) | 0.272 (0.56) | 0.04* | | | |
| Knee external rotation moment | EFG | -0.17 (0.074) | 0.153 (0.61) | 0.73 | 0.12 (0.814) | 0.49 (0.263) | 0.04 (1.028) |
| during stance phase (Nm/kg × i | CG | -18 (0.63) | -0.531 (0.90) | 0.16 | | | |
| | FG | 0.249 (1.33) | -1.64 (1.71) | 0.013* | | | |
| Knee adduction moment during | EFG | -1.16 (0.82) | -1.20 (1.63) | 0.94 | 0.19 (0.714) | 0.12 (0.617) | 0.005 (0.137) |
| stance pnase (Nm/kg*m) | CG | -0.327 (1.84) | 0.210 (1.83) | 0.19 | | | |

TABLE 2. Means (standard deviations) of kinetic and kinematic parameters of the knee joint during the stance phase of gait in the experimental groups.

CG, Control group; FG, Functional stretching; EFG, Extra-functional stretching; ROM, Range of motion. *Significant difference.

pairwise comparison revealed increased cadence after extrafunctional stretching (p = 0.005) (Table 2). Also, the results demonstrated significant time \times group interaction for knee flexion-extension ROM during the stance phase (p =0.013, d = 1.22; pairwise comparison revealed increased knee flexion-extension ROM during the stance phase after functional stretching (p = 0.03). There was not any significant main effect of group or time, nor any significant time \times group interaction, for knee flexion angle at initial contact (*p* > 0.05) (Table 2), but we found significant time \times group interaction for the knee external rotation moment during the stance phase (p = 0.04, d = 1.028); pairwise comparison showed increased knee external rotation moment during the stance phase after functional stretching (p = 0.04) (Table 2). Finally, we found significant time \times group interaction for the knee adduction moment during the stance phase (p =0.005, d = 1.37); pairwise comparison showed decreased knee adduction moment during the stance phase after functional stretching (p = 0.013) (Table 2).

4. Discussion

A reduction in the external rotation moment of the knee through an eight-week functional stretching program was the major finding of the present study (Table 2). The knee joint has internal–external rotation in the horizontal plane in addition to motion in the sagittal plane. During the last 10–15 degrees before complete extension, internal rotation of the medial femoral condyle and external rotation of the tibia occur. At the same time, the lateral meniscus is anteriorly translated and the medial meniscus is posteriorly translated. Since the medial tibiofemoral joint has a larger contact surface, the length of the medial femoral condyle is greater than that of the lateral. Also, the limitations of cruciate–collateral ligaments and quadriceps femoris on knee motion result in the knee joint self-locking as an eccentric wheel to maintain the stability of the joint during the knee extension motion [8].



FIG. 2. The Knee Joint Moments during stance phase of gait. (a) Knee adduction moment in the frontal plane. (b) Knee external rotation moment in the horizontal plane of both groups in pre-test/post-test during the stance phase of gait.

Regarding the importance of the external moment of the knee, Wu *et al.* [20] stated that abnormal external rota-

tion of the knee during the stance phase is a common cause of lateral deviation of the patella in people with gastrocsoleus complex shortness, which is a known risk factor for patellofemoral pain. In this regard, according to the findings of this study, functional stretching of the gastroc-soleus muscle complex may be effective (Fig. 2). Further research is needed to confirm the effectiveness of this training program. Understanding the mechanism of reducing the knee external rotation moment during gait with increased heel strike is more important for us. One possible interpretation of this finding may be related to the increased heel-off duration among the functional stretching group. It is believed that increased DF ROM, as found in the present study with an increased heel-off duration, is associated with reduced forefoot peak plantar pressure and relieves stress from soft tissue [12, 23]. Perhaps walking with increased heel strike, as a functional model in CKC that follows the specificity principle of training, is successful in changing the mechanics of the ankle joint during the gait cycle, as well as reducing the knee external rotation moment. However, studying the effect of an increased heel strike gait pattern mechanism on reducing the knee external rotation moment is important for future research. Another explanation for this finding may lie in improvement of the muscle's activation pattern following functional stretching exercises in which movement is rehabilitated as a whole anatomical unit [13]; according to Lederman 2014, ROM rehabilitation that favors movement fragmentation, like extra-functional stretching exercises, is more likely to improve specific fragmented activity but not the whole movement like functional stretching exercises. In the present study we did not investigate the muscular activity before and after the intervention, so further studies are needed to explore the effect of functional and extrafunctional stretching exercises on lower extremity muscle activity patterns.

Our findings indicated that eight weeks of functional stretch training in individuals with limited DF led to increased knee flexion during the stance phase. Also. despite the non-significant effect of the extra-functional stretching on knee flexion during the stance phase, the results showed that in the extra-functional group, the knee flexion angle during the stance phase decreased. It is important to note that in previous studies such as Wu et al. [28] and You et al. [3], increased knee flexion angle during the stance phase was suggested as a compensatory pattern due to the tightness of the gastroc-soleus muscle complex. However, the application of both functional and extrafunctional stretching programs in this study led to increased knee flexion angle during the stance phase, which is an unexpected finding of the present study. The explanation for this finding lies in Mercer et al. [29]. Although we did not measure the exact pattern of heel contact with the ground in athletes, our research findings are consistent with those of Mercer et al. [29]. They implied that not only do some runners have a tendency to toe-walk, which is a contributing factor for gastroc-soleus muscle tightness, but they also use compensatory movement patterns in other

joints of the kinetic chain, such as increased knee extension during the stance phase. In this way, their mechanical energy is more efficient [29, 30]. On the other hand, Ota et al. [11] identified repeated knee extension as a factor affecting excessive loading of the posterior capsule of the knee joint, and stated that repetitive knee loading would lead to genu recurvatum and ACL injury. Therefore, it might be said that the functional stretching program could be effective in reducing repetitive loading of the posterior capsule of the knee joint in athletes with limited ankle DF. However, more research is needed to confirm further aspects of this issue. Although the decrease in the knee flexion range in the extra-functional group was not significant, the knee flexion angle in this training group showed a slight decrease, indicating the effectiveness of the extra-functional stretching program in reducing the knee flexion angle (Fig. 3). A comparison between the groups confirmed that the functional stretching program was more effective in decreasing the knee flexion angle during the stance phase compared with the extra-functional stretching program.



FIG. 3. The knee joint angles during stance phase of gait. (a) Flexionextension degree pattern in the sagittal plane. (b) Abduction-adduction degree pattern in the frontal plane of both groups in pre-test/post-test during the stance phase of gait.

The results of the present study showed that the mean of the knee adduction moment in the functional stretching group was significantly reduced, but the reduction was not significant in the extra-functional stretching group. The knee adduction moment corresponds to the product of the ground reaction force, acting through the foot and medial to the knee joint, and the perpendicular distance from the ground reaction force to the axis of knee joint abduction and adduction movement [31]. There is also a higher incidence of knee osteoarthritis (OA) in the medial than the lateral compartment of the knee [32]. Patients having a knee with OA present greater peak knee adduction moment and frontal plane lever arm (perpendicular distance between the ground reaction force and the knee joint center) but less ground reaction force [32]. So, one can conclude that the functional stretching

program may be effective in preventing OA. Due to the lack of literature on the subject, this result cannot be compared with others. However, it can be explained that the stride length and speed are related with the joint moment. Alet *et al.* [15] stated that the joint moment is one of the key factors in understanding and recognizing movement disorders in the gait cycle, suggesting that stride speed is one of the critical factors influencing the joint moment. We consider that the significant increase in stride length in both training groups in the present study is consistent with the results of Gajdosik *et al.* [24], and the walking speed was significantly increased in the extra-functional group, but the decrease in the functional group was not significant.

Our hypothesis about decreasing knee joint loading following the functional stretching program was accepted in terms of the knee external rotation moment and the knee adduction moment, but it was not accepted in terms of the knee flexion moment. It would be difficult to comment on whether the type of training program could reduce the knee adduction moment or stride length and speed, leading to reduced knee joint adduction. The safety and effectiveness of the functional stretching program in reducing knee joint mechanical forces and consequently reducing joint loading along the kinetic chain was the most important factor in this research. To our knowledge, the present study is one of few articles investigating the effectiveness of a functional stretching program in people with gastroc–soleus muscle complex tightness.

5. Limitations

A limitation of the present study was the use of self-selected walking speeds, which probably influenced the effectiveness of the results. Also, considering that the participants of this study were runners with a special gait pattern, one should be cautious in generalizing the results of this study to others.

6. Conclusions

The results of this study showed that a fine change in the mechanical position of the ankle joint in the sagittal plane can lead to decreased knee loading in the frontal and horizontal planes. This suggests the importance of an increased heel strike gait pattern in individuals with limited ankle DF.

Abbreviations

ACL, Anterior Cruciate Ligament; CKC, Closed Kinetic Chain; DF, Dorsi Flexion; OA, Osteoarthritis; OKC, Open Kinetic Chain; ROM, Range of Motion.

Author contributions

RF and SSS conceived and designed the experiments. FR performed the experiments. FR, GB and SSS analyzed the data. FR and SSS contributed reagents and materials. FR, SSS and GB wrote the paper.

Ethics approval and consent to participate

All procedures performed in studies involving human participants were in accordance with the ethical standards of institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

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Conflict of interest

The authors declare no conflict of interest.

References

- Araújo VL, Carvalhais VOC, Souza TR, Ocarino JM, Gonçalves GGP, Fonseca ST. Validity and reliability of clinical tests for assessing passive ankle stiffness. Revista Brasileira de Fisioterapi. 2011; 15: 166–173.
- Huguenin LK. Myofascial trigger points: the current evidence. Physical Therapy in Sport. 2004; 5: 2–12.
- [3] You J-Y, Lee H-M, Luo H-J, Leu C-C, Cheng P-G, Wu S-K. Gastrocnemius tightness on joint angle and work of lower extremity during gait. Clinical Biomechanics. 2009; 24: 744–750.
- [4] Mason-Mackay AR, Whatman C, Reid D. The effect of reduced ankle dorsiflexion on lower extremity mechanics during landing: a systematic review. Journal of Science and Medicine in Sport. 2017; 20: 451–458.
- [5] Page P, Frank C, Lardner R. Assessment and treatment of muscle imbalance: the Janda approach. Human Kinetics. 2010.
- [6] Tabrizi P, McIntyre WMJ, Quesnel MB, Howard AW. Limited dorsiflexion predisposes to injuries of the ankle in children. The Journal of Bone and Joint Surgery. 2000; 82: 1103–1106.
- [7] Boonchum H, Bovonsunthonchai S, Sinsurin K, Kunanusornchai W. Effect of a home-based stretching exercise on multi-segmental foot motion and clinical outcomes in patients with plantar fasciitis. Journal of Musculoskeletal & Neuronal Interactions. 2020; 20: 411–420.
- [8] Zhang L, Liu G, Han B, Wang Z, Yan Y, Ma J, et al. Knee joint biomechanics in physiological conditions and how pathologies can affect it: a systematic review. Applied Bionics and Biomechanics. 2020; 2020: 1–22.
- [9] Piva SR, Goodnite EA, Childs JD. Strength around the hip and flexibility of soft tissues in individuals with and without patellofemoral pain syndrome. Journal of Orthopaedic & Sports Physical Therapy. 2005; 35: 793–801.
- [10] Moseley AM, Crosbie J, Adams R. High- and low-ankle flexibility and motor task performance. Gait & Posture. 2003; 18: 73–80.
- [11] Ota S, Ueda M, Aimoto K, Suzuki Y, Sigward SM. Acute influence of restricted ankle dorsiflexion angle on knee joint mechanics during gait. The Knee. 2014; 21: 669–675.

- [12] Macklin K, Healy A, Chockalingam N. The effect of calf muscle stretching exercises on ankle joint dorsiflexion and dynamic foot pressures, force and related temporal parameters. The Foot. 2012; 22: 10–17.
- [13] Lederman E. Therapeutic stretching towards a functional approach. 1st ed. London: Elsevier. 2014.
- [14] Ghasemi E, Khademi-Kalantari K, Khalkhali-Zavieh M, Rezasoltani A, Ghasemi M, Baghban AA, *et al.* The effect of functional stretching exercises on functional outcomes in spastic stroke patients: a randomized controlled clinical trial. Journal of Bodywork and Movement Therapies. 2018; 22: 1004–1012.
- [15] Allet L, IJzerman H, Meijer K, Willems P, Savelberg H. The influence of stride-length on plantar foot-pressures and joint moments. Gait & Posture. 2011; 34: 300–306.
- [16] Youdas JW, Krause DA, Egan KS, Therneau TM, Laskowski ER. The effect of static stretching of the calf muscle-tendon unit on active ankle dorsiflexion range of motion. Journal of Orthopaedic & Sports Physical Therapy. 2003; 33: 408–417.
- [17] Neptune RR, Zajac FE, Kautz SA. Muscle force redistributes segmental power for body progression during walking. Gait and Posture. 2004; 19: 194–205.
- [18] Neptune RR, Kautz SA, Zajac FE. Contributions of the individual ankle plantar flexors to support, forward progression and swing initiation during walking. Journal of Biomechanics. 2001; 34: 1387–1398.
- [19] Bell-Jenje T, Olivier B, Wood W, Rogers S, Green A, McKinon W. The association between loss of ankle dorsiflexion range of movement, and hip adduction and internal rotation during a step down test. Manual Therapy. 2016; 21: 256–261.
- [20] Wu S-K, Lou S-Z, Lee H-M, Chen H-Y, You J-Y. Gastrocnemius inflexibility on foot progression angle and ankle kinetics during walking. Clinical Biomechanics. 2014; 29: 556–563.
- [21] Lewis CL, Garibay EJ. Effect of increased pushoff during gait on hip joint forces. Journal of Biomechanics. 2015; 48: 181–185.
- [22] Norkin CC, White DJ. Measurement of joint motion: a guide to goniometry. 2 nd edition philadelphia: F.A Davis Company. 2003.

- [23] Johanson M, Baer J, Hovermale H, Phouthavong P. Subtalar joint position during gastrocnemius stretching and ankle dorsiflexion range of motion. Journal of Athletic Training. 2008; 43: 172–178.
- [24] Gajdosik RL, Vander Linden DW, McNair PJ, Williams AK, Riggin TJ. Effects of an eight-week stretching program on the passive-elastic properties and function of the calf muscles of older women. Clinical Biomechanics. 2005; 20: 973–983.
- [25] Guissard N, Duchateau J. Effect of static stretch training on neural and mechanical properties of the human plantar-flexor muscles. Muscle & Nerve. 2004; 29: 248–255.
- [26] Sahrmann S. Diagnosis and treatment of movement impairments syndromes. 1st ed. Maryland: Mosby. 2002.
- [27] Gruber AH, Edwards WB, Hamill J, Derrick TR, Boyer KA. A comparison of the ground reaction force frequency content during rearfoot and non-rearfoot running patterns. Gait & Posture. 2017; 56: 54–59.
- [28] Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, et al. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine. Journal of Biomechanics. 2002; 35: 543–548.
- [29] Mercer JA, Horsch S. Heel-toe running: a new look at the influence of foot strike pattern on impact force. Journal of Exercise Science & Fitness. 2015; 13: 29–34.
- [30] Gajdosik RL, Allred JD, Gabbert HL, Sonsteng BA. A stretching program increases the dynamic passive length and passive resistive properties of the calf muscle-tendon unit of unconditioned younger women. European Journal of Applied Physiology. 2007; 99: 449–454.
- [31] Thorstensson CA, Henriksson M, von Porat A, Sjödahl C, Roos EM. The effect of eight weeks of exercise on knee adduction moment in early knee osteoarthritis—a pilot study. Osteoarthritis and Cartilage. 2007; 15: 1163–1170.
- [32] Timothy L N, Joel H, Michael R G, J David B. Knee loading due to varus and external rotation in gait supports medial compartment wear in total knee arthroplasty. Journal of Orthopedics and Rheumatism. 2017; 1: 8–18.