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ORIGINAL RESEARCH

EFFECTS OF A MOVEMENT TRAINING PROGRAM ON HIP AND KNEE JOINT FRONTAL PLANE RUNNING MECHANICS

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ABSTRACT

Background/Purpose: Frontal plane running mechanics may contribute to the etiology or exacerbation of common running related injuries. Hip strengthening alone may not change frontal plane hip and knee joint running mechanics. The purpose of the current study was to evaluate whether a training program including visual, verbal, and tactile feedback affects hip and knee joint frontal plane running mechanics among females with evidence of altered weight bearing kinematics.

Methods: The knee frontal plane projection angle of 69 apparently healthy females was determined during a single leg squat. The twenty females from this larger sample who exhibited the most acute frontal plane projection angle (medial knee position) during this activity were chosen to participate in this study (age = 20 ± 1.6 years, height = 167.9 ± 6.0 cm, mass = 63.2 ± 8.3 kg, Tegner Activity Rating mode = 7.0). Participants engaged in a 4-week movement training program using guided practice during weight bearing exercises with visual, verbal, and tactile feedback regarding lower extremity alignment. Paired t-tests were used to compare frontal plane knee and hip joint angles and moments before and after the training program.

Results: After training, internal hip and knee abduction moments during running decreased by 23% ($P = 0.007$) and 29% ($P = 0.033$) respectively. Knee adduction and abduction excursion decreased by 2.1° ($P = 0.050$) and 2.7° ($P = 0.008$) respectively, suggesting that less frontal plane movement of the knee occurred during running after training. Peak knee abduction angle decreased 1.8° after training ($P = 0.051$) although this was not statistically significant. Contralateral peak pelvic drop, pelvic drop excursion, peak hip adduction angle, hip adduction excursion, and peak knee adduction angle were unchanged following training.

Conclusions: A four week movement training program may reduce frontal plane hip and knee joint mechanics thought to contribute to the etiology and exacerbation of some running related injuries.

Level of Evidence: Level 4

Keywords: female, kinematics, kinetics, neuromuscular training, rehabilitation

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INTRODUCTION

The benefits of regular exercise are widely described and may lead people to engage in activities such as running. It is estimated that over 35 million Americans use running as a mode of regular physical activity.[1] However, 19-79% of these runners may experience an injury each year.[2] Altered frontal plane hip and knee joint mechanics during the stance phase of running may contribute to the etiology of many common running injuries. For example, increased hip adduction angle, internal hip abduction moment, and internal knee abduction angular impulse have been reported among runners with patellofemoral pain.[3,4] Additionally, high peak hip adduction angles during running may increase a runner's risk of developing tibial stress fractures and iliotibial band syndrome.[5,6] Clinically-oriented interventions to reduce these altered frontal plane running kinetics and kinematics may be valuable for rehabilitation of such individuals who sustain these running related injuries.

Hip muscle strength appears to have little association with altered frontal plane running mechanics. Focused training studies to increase hip abduction and external rotation strength have not decreased hip or knee frontal plane peak joint angles or joint excursions during the stance phase of running.[7,8] Further, a low correlation has been reported between hip strength and frontal plane hip and knee peak angles and joint motions during running and jumping.[9,10] The clinical relevance of these studies is that hip strengthening alone may not be an effective remedy for altered lower extremity running mechanics that may increase the risk of running related injury.

It may be necessary for clinical interventions to incorporate elements intended to affect neuromuscular control of muscles that may diminish altered frontal plane running mechanics. Such elements may include guided practice using visual, verbal, or tactile feedback of movement performance. For example, females with patellofemoral pain (PFP) demonstrated significantly less peak hip adduction while running at the end of a 2-week training program where participants were provided visual feedback of three-dimensional hip kinematics during running.[11] Additionally, a 14-week rehabilitation program for PFP that included visual feedback and hip strengthening exercises was also found to decrease pain and hip adduction angle for an individual with PFP during a single leg step down.[12] Finally, peak hip adduction and knee abduction angles during a drop jump activity decreased among subjects who received visual feedback for altering movement performance and strength training.[13] Subjects who received the strength training intervention alone did not experience these changes.[13]

A home-based training program to reduce hip and knee joint frontal plane motion and peak moments may be of value to clinicians seeking to improve altered running mechanics observed in their patients. Based on the available evidence, it seems such a program should emphasize neuromuscular control elements such as guided practice of movement performance and visual, verbal, and tactile feedback rather than hip strengthening alone. Unfortunately, the authors are aware of only a single previous study that has emphasized visual and verbal feedback in a home-based exercise program with the goal of improving running mechanics.[14] This study reported that peak hip adduction angle and contralateral pelvic drop did not change at the conclusion of a six-week program that included four weeks of visual and verbal feedback during weight bearing exercises traditionally used for hip strengthening.[14] However, changes in knee joint mechanics were not included in the results of their study. Therefore, the purpose of the current study was to evaluate whether a training program including visual, verbal, and tactile feedback affects hip and knee joint frontal plane running mechanics among females with evidence of altered weight bearing kinematics. The authors hypothesized that after training, the participants would demonstrate decreased frontal plane hip and knee joint peak angles, excursion, and moments during running.

METHODS

Subjects:

Using $\alpha = 0.05$, $\beta = 0.2$, and a recent estimate of hip and knee joint frontal plane kinematic variability during running,[15] we determined that 18 subjects were necessary to identify changes in frontal plane running kinematics of greater than 2.8° after training (effect size > 0.7). A more medial knee position during weight bearing activities has been associated with both acute and chronic knee injuries.[15,16,17,18]

Thus, the authors aimed to enroll females who clearly demonstrated this movement characteristic during a single leg squat as they may have been more likely to demonstrate altered running kinematics, experience overuse knee injuries, and therefore benefit from a structured neuromuscular training program intended to change altered weight-bearing mechanics (prior to or after injury).[2,15] To find these 18 females, the authors screened 69 active and apparently healthy females with an age range of 18-25 years who were recruited from a university population. No potential subject had a history of chronic or accidental injury over the last 6 months. Each subject was a regular participant in weight-bearing exercises that may have included recreational sports, cardiovascular training, or weight training at least 3 times/week for ≥30 min. Exclusion criteria included reports of lower extremity injury within the last 3 months requiring medical treatment, history of lower extremity surgery within the last 12 months, or pain or restriction with running, jumping, or stair negotiation. Appropriate ethical approval had been granted from an institutional review board prior to the commencement of the study and all participants provided their informed consent prior to participation.

Two-Dimensional (2D) Analysis:
To determine which subjects demonstrated the greatest medial knee position during a single leg squat, 2D medial knee position was recorded with a digital camera (Samsung model L200, Samsung Electronics, Ridgefield, NJ USA) for all 69 female volunteers during a step-down task using a 20.3 cm step. This measurement has been described as frontal plane projection angle (FPPA).[15] The camera was leveled and placed on a tripod at a height of 70 cm from the floor, 7.6 m to the front and perpendicular to the 20.3 cm step. Each participant wore the same shoe model (Running shoe model 629, New Balance Boston, MA, USA) to avoid variability in different sole materials between subjects and testing sessions. Two millimeter adhesive markers were placed only on the dominant leg (preferred leg used to kick a ball as far as possible). A tape measure was used to bisect the ankle malleoli and femoral condyles. Markers were placed at these identified midpoint locations. The tape was then used to form a line from the anterior superior iliac spine (ASIS) to the knee joint marker and a marker was placed on this line approximately 30 cm above the knee marker. Next, subjects were provided both a demonstration and verbal instruction of the step down without specific directions regarding knee and hip alignment. Each step down was to be completed over a 5-s interval[15] from descent to ascent paced by a digital metronome (Qt 3 Digital Metronome, Model 96204X, Mel Bay Publications Pacific, MO) set at a rate of 60 beats/minute. The initiation of the step down occurred at 1 s (beat 1), lowering their non-stance leg until their heel lightly touched the floor in front of the step at 3 s (beat 3), and finishing in a standing position at 5 s (beat 5). A digital picture was taken at the second metronome beat during each performance trial. After demonstrating adequate skill, subjects performed 5 trials for analysis. There was a 60 second rest period between practice trials and the 5 test trials. The FPPA was calculated by measuring the angle formed by lines drawn on the image between the thigh and knee markers and between the ankle and knee markers (CorelDraw v11.6, Corel Corporation, Ottawa, Ontario, Canada) (Fig. 1). Average FPPA value from the 5 trials was calculated for each subject. Knee markers medial to thigh and ankle markers were assigned negative FPPA values while knee markers in a lateral position were assigned positive FPPA values. Of the original 69 volunteers, 20 subjects with the most acute negative FPPA values were invited to participate in the training program [FPPA = –8.5° (range = –4.5° to –15.3°, sd = 2.6°), age = 20.0 yr (sd = 1.6 yr), height = 167.9 cm (sd = 6.0 cm), mass = 63.2 kg (sd = 8.3 kg), Tegner Activity Rating mode = 7.0 (range = 5–9)]. The FPPA measured among these 20 participants was consistent with the FPPA reported among female runners with patellofemoral pain in a previous study.[15] Twenty subjects were chosen to account for the possibility of dropouts associated with the nature of the training portion of this investigation. Eighteen of these 20 subjects participated in all phases of the study and were included in the statistical analysis (Fig. 2).

Three Dimensional (3D) analysis of running mechanics:
Lower extremity mechanics were recorded as subjects ran along a 23 meter runway. Specifically, reflective tracking markers were placed on the right and left ASIS, the sacrum, the right and left posterior

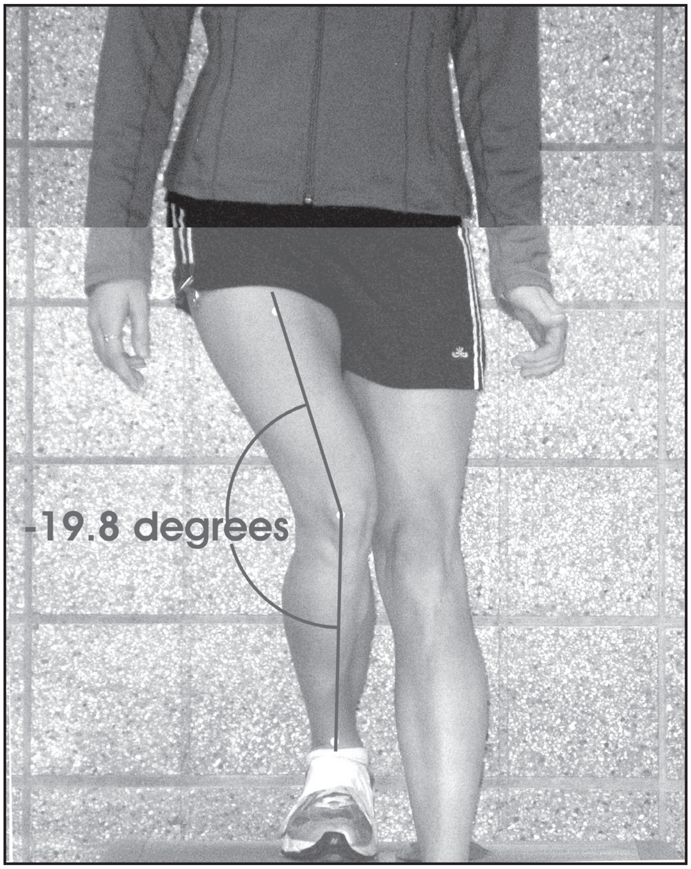

Figure 1. *Markers used to determine the frontal plane projection angle (FPPA) during single leg step downs.*

superior iliac spine, the anterior thigh, the lateral femoral condyle, the tibial tuberosity, anterior shank along the tibial plateau, the lateral malleolus, and the dorsum of the foot, heel, and superior surface of the 2nd metatarsal of each subject's shoe. Temporary markers on the medial femoral condyle and medial malleolus were also used to mark the segment endpoints, which were removed prior to running trials. The 3D marker coordinate data were captured at 240 Hz using an 8 camera motion analysis system (Motion Analysis Corporation, Santa Rosa, CA, USA). These data were smoothed at 12 Hz using a 4th order recursive Butterworth low pass filter. Hip and knee joint kinematics were calculated from the local coordinate data using Motion Monitor Software (Version 7.0, Innovative Sports Training, Chicago, IL, USA). The subjects were asked to run between 3.52 and 3.89 m/s as indicated by feedback from the investigator immediately after each trial regarding the average forward velocity of the sacral marker over the last 9 video frames of terminal swing prior to contact with the

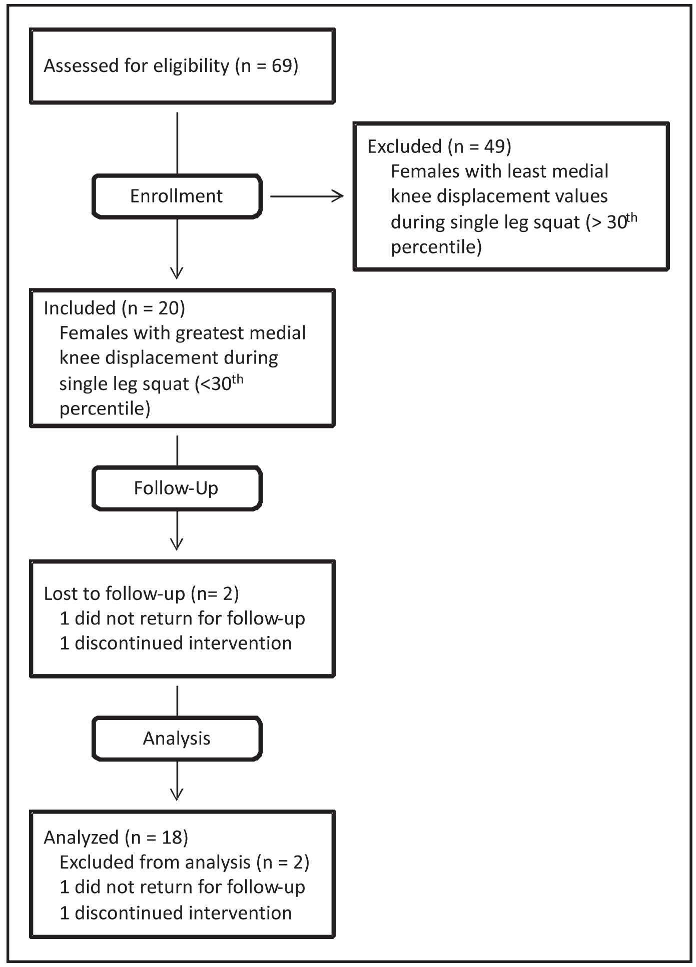

Figure 2. *Flowchart of subject progression in this pre-test, post test quasi-experimental design.*

force platform. Ground reaction forces were recorded at 1080 Hz by a force platform (Model 4080, Bertec Corporation, Columbus, OH, USA) flush with the surface of the runway. These analog data were filtered at the same cutoff frequency as the kinematic data. The inverse dynamics approach was used to calculate frontal plane hip and knee internal joint moments. Each subject completed five practice trials, followed by five trials collected for use in data analysis. The average peak value for these kinematic and kinetic variables during the five trials were determined for the stance phase of the running cycle.

Neuromuscular Training:

Subjects participated in a 4-week movement training program using exercises adopted from previous training programs with an emphasis on gluteus medius

Table 1. *Exercise progression utilized during 4-week neuromuscular training program. Subjects received personal instruction and verbal and visual (mirror) feedback of movement performance during all exercises one time/week. Instructions provided to participants included keeping the knee in line with the hip and foot in the frontal plane, the pelvis parallel with the floor, and to increase hip flexion to avoid anterior motion of the knee beyond the foot during squat exercise performance. Single leg exercises were performed on dominant leg only. All exercises were performed independently at home an additional two times/week with use of a mirror.*

	Exercise	Volume	Instructions
Week 0-1	Wall or form squat	3 x 10 reps	Bend knees to 90°, hold 5 seconds
	Forward lunge	3 x 10 reps	Step forward with dominant leg and bend knees to 90°
	Lateral step-down 4" step	3 x 10 reps	Stand on step, lower non-dominant foot to floor but do not touch the floor
	Single-leg stance with ball toss	3 x 30 s	Knee slightly bent, throw ball forward against a wall or to a partner
Week 1-2	Lateral step-down 7" step	3 x 10 reps	Stand on step, lower non-dominant foot to floor but do not touch the floor
	Forward step-up 7" step	3 x 10 reps	Facing step, raise up onto dominant leg, lower non-dominant heel back to floor
	Single-leg deadlift	3 x 10 reps	Knee slightly bent, touch floor in front of foot with both hands
	Lateral shuffles with theraband	3 x 40 ft	Elastic around and above both knees, walk laterally with knees slightly flexed
Week 2-4	Forward step-down 7" step	3 x 10 reps	Stand on step, lower non-dominant foot to floor but do not touch the floor
	Balance lunge	3 x 10 reps	With non-dominant leg on chair behind you, step forward and flex knee to 90°
	Single-leg multidirectional reach	3 x 5 reps	Knee slightly bent, touch floor in front of foot with both hands. Repeat to locations on floor at 45° medially and laterally
	Single-leg squat with theraband	3 x 10 reps	Elastic around and above both knees, stand on dominant leg and bend knee to 60°. Contralateral knee is flexed and hip is maintained in slight abduction.

and gluteus maximus facilitation techniques believed to influence lower extremity alignment and foster hip and knee joint neuromuscular control (Table 1).[19,20,21,22] To isolate the neuromuscular effects of the intervention, the training program in this study was limited to 4 weeks to limit the potential influence of hypertrophic muscle changes on running mechanics. Subjects received personal instruction and verbal and visual (using a mirror) feedback during movement performance of all exercises from a licensed physical therapist one time/week. Instructions provided to participants included keeping the knee in line with the hip and foot in the frontal plane, the pelvis parallel with the floor, to increase hip flexion to avoid anterior motion of the knee beyond the foot during squat exercise performance, and to maintain a neutral lumbar spine. Therapists also employed manual neuromuscular facilitation techniques at each visit such as tapping over the gluteal muscles or tactile feedback to the lateral knee to promote hip abduction during instruction in these exercises. All exercises were performed once a week with the therapist and independently at home an additional two times/week with use of a mirror. A home exercise log was used to foster and monitor exercise compliance outside the weekly guided exercise sessions. To standardize results from the training program, all subjects followed the same exercise progression (Table 1). Participants were allowed to participate in other exercise routines or recreational activities as desired. After the 4-week training period, subjects returned for post-testing where no specific directions regarding lower extremity alignment were provided during the running performance trials.

Statistics:
Ten paired samples t-statistics ($\alpha = 0.05$) were used to compare pelvis, hip, and knee peak frontal plane angles and excursion (frontal plane motion from initial contact to peak angle during the stance phase) and peak hip and knee internal joint moments before and after the movement training program. Effect sizes were calculated to illustrate the magnitude of change in these variables. All statistical procedures were performed in SPSS (version 17, SPSS Inc., Chicago, IL).

RESULTS

Eighteen of 20 subjects completed all phases of the study including movement training and post-testing. According to exercise logs kept by each subject, there was 100% compliance in exercise performance three times/week, and 85% compliance in using a mirror to provide visual feedback on lower extremity alignment when performing the exercises.

Following the four week movement training program there were notable changes in hip and knee frontal plane moments. Specifically, internal hip and knee abduction moments decreased by 23% (effect size = 0.74, P = 0.007), and 29% (effect size = 0.71, P = 0.033), respectively (Figure 3, Table 2). After training, participants also tended to demonstrate a more lateral position of the knee during running as evidenced by a 1.8° decrease in peak knee abduction angle (effect size = 0.50, P = 0.051), a

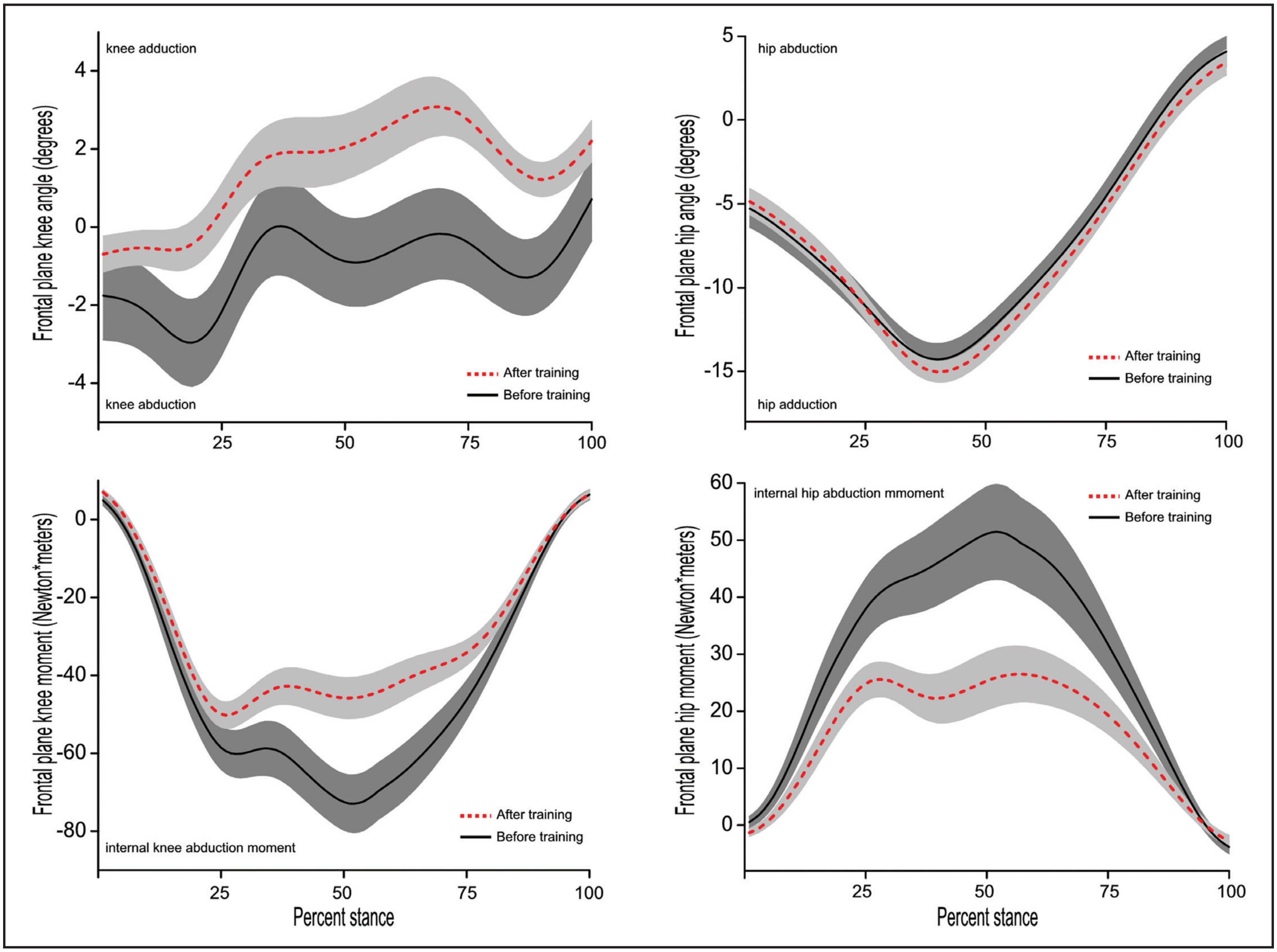

Figure 3. *Time normalized hip and knee angles and internal joint moments during the stance phase of running among participants before and after the 4 week movement training intervention. The shaded regions represent 1 standard error of the mean at each time point.*

Table 2. *Average (SD) hip and knee joint frontal plane peak angles, excursions, and internal joint moments during running before and after training among females who participated in the movement training program.*

Joint kinematics Average (SD), in degrees	Before training	After training	*P*-value	Effect Size
Peak pelvic drop angle	8.5 (2.9)	8.5 (2.7)	0.51	0
Pelvic drop excursion	4.0 (3.0)	4.0 (2.9)	0.81	0
Peak hip adduction angle	14.5 (3.5)	14.4 (3.5)	0.90	0.03
Hip adduction excursion	8.5 (4.0)	8.5 (3.3)	0.71	0
Peak knee abduction angle	3.3 (4.0)	1.5 (3.2)	0.051	0.50
Knee abduction excursion	3.3 (2.9)	0.6 (1.7)	0.008	1.17
Peak knee adduction angle	4.7 (4.2)	6.1 (3.5)	0.14	0.36
Knee adduction excursion	4.4 (4.1)	6.5 (4.1)	0.050	0.51
Joint moments Average (SD), in Nm				
Peak hip abduction moment	49.2 (18.5)	37.7 (12.6)	0.007	0.74
Peak knee abduction moment	80.1 (37.1)	56.5 (29.3)	0.033	0.71

2.1° increase in knee adduction excursion (effect size = 0.51, P = 0.050), and a 2.7° decrease in knee abduction excursion (effect size = 1.17, P = 0.008). However, no changes were identified in peak contralateral pelvic drop angle or excursion, peak hip adduction angle or excursion, or peak knee adduction angle. (Table 2)

DISCUSSION

The purpose of the current study was to evaluate whether a movement training program using visual feedback and weekly instruction and manual facilitation of lower extremity alignment affects hip and knee joint frontal plane running mechanics among females with evidence of altered weight bearing kinematics. At the end of this 4-week training program, participants displayed decreased internal hip and knee abduction joint moments, decreased knee abduction excursion, and increased knee adduction excursion during stance while running. The intervention in this study translates well to clinical practice because it does not utilize special equipment and requires relatively few visits with the therapist. As such, these findings may be relevant to clinicians looking for methods to improve altered running mechanics observed in their patients.

Increased frontal plane hip and knee joint moments have been identified among individuals with overuse injuries and degenerative conditions such as patellofemoral pain and medial compartment knee osteoarthritis.[3,4,23] It has been hypothesized that increased internal hip and knee abduction moment during running results in greater force on the lateral facet of the patella through greater contributions from the vastus lateralis, extensions of the iliotibial band, or both.[4] Greater force on the patella from these tissues may result in greater retropatellar stress and activation of nociceptive fibers in patellar subchondral bone or synovium.[3,4] Decreasing frontal plane hip or knee joint moments during running may therefore have clinical relevance by reducing retropatellar stress and symptoms experienced by individuals during routine exercise. However, to the authors knowledge only two previous studies report effects of exercise interventions to reduce hip and knee joint moments during running.[24,25] Snyder et al reported that a 6-week hip strengthening program was associated with a 10% decrease in knee abductor moment during running.[24] Earl et al reported 15% and 23% decreased internal hip and knee abductor moments during running, respectively following an 8-week "proximal stability program" that included five weeks of training including attention to lower extremity alignment during exercises for patellofemoral pain.[25] Following the movement training provided in this study, internal hip and knee abduction moments decreased by 23% and 29%, respectively. The relatively large training effects found in both the present study and by Earl et al support the notion that attention to lower extremity alignment may be a more important component of interventions used to modify running mechanics than interventions that include strengthening alone.

In addition to smaller frontal plane internal hip and knee joint moments, participants also demonstrated less knee abduction excursion and increased knee adduction excursion during the stance phase of running after the movement training program. These effects suggest a less medial knee position during running that may be beneficial for the participants who demonstrated the most negative (medial) frontal plane projection angles displayed during a single leg squat. A medial knee position during the stance phase of running may affect the line of pull of the quadriceps and contribute to the etiology or exacerbation of overuse injuries such as patellofemoral pain.[18,26,27] As such, this finding may be relevant for clinicians working with runners who experience this condition. Interestingly, to the authors' knowledge, no previous studies of exercise-based programs used to modify running kinematics have reported significant changes in frontal plane knee angles or excursions. This novel finding may be related to the method used for participant selection. The subjects who were selected demonstrated the most medial knee position during a single leg squat activity. Therefore, it is possible that these participants had the greatest capacity for changing lower extremity kinematics and kinetics during the stance phase of running. Previous studies that have reported frontal plane knee joint kinematics following a hip strengthening or proximal stability training program did not screen potential subjects for evidence of altered weight bearing kinematics.[8,24,25] As such, it may be reasonable to expect less change in such participants.

Despite kinematic and kinetic changes observed at the knee joint, the participants in the current study did not demonstrate changes in peak hip adduction or hip adduction excursion while running after the movement training program. This finding is consistent with three previous studies that also have reported no changes in frontal plane hip motion during running following a training program attempting to alter running mechanics.[24,25,14] It has been suggested that to successfully alter running mechanics it may be necessary to include neuromuscular training during running within the exercise program.[14] Both the interventions used in the current study and the intervention associated with three previous studies did not include feedback while actually running. To date, only one previous intervention to improve altered running mechanics included movement feedback during running. In that study, Noehren et al reported that 2-weeks of training using three-dimensional movement feedback during running resulted in decreased peak hip adduction during running among ten runners with patellofemoral pain.[11] While this finding is notable because it suggests a plausible mechanism for changing hip joint running kinematics, future investigations may consider alternative methods to 3-D analysis that could provide performance based feedback during running that are feasible for widespread use in clinical settings. It is also worthwhile to highlight that although frontal plane hip joint kinematics were not affected by the training program utilized in the current study, frontal plane knee kinematics and kinetics were. Therefore, the results of the current study conflict somewhat with the premise that movement patterns emphasized during guided exercise programs do not transfer to running. Future studies are necessary to cross validate these findings and delineate the role of specificity of training on running mechanics.

The intervention in the current study was intended to limit the potential influence of muscle hypertrophic changes associated with exercise. Previous studies with the intent of changing running mechanics utilized interventions that lasted between 6 and 14 weeks.[12,24,25] Based on the length of these studies, it is difficult to determine whether these changes observed in running mechanics were a result of hypertrophic strength gains or altered neuromuscular recruitment patterns. It has been suggested that increases in muscle force measured after fewer than five weeks of training are largely due to neuromuscular adaptations, whereas changes noted after five weeks are more closely associated with hypertrophic changes.[28] Therefore, the gains seen in the current study are believed to occur primarily through neuromuscular adaptations as a result of task performance. However, electromyographic analysis would be necessary to confirm or refute that the changes following this training program were associated with changes in lower extremity muscle activation level or timing during running.

The current study adds to a growing body of evidence for the effectiveness of using guided practice consisting of visual, verbal, and tactile feedback to modify movement patterns, but does not fully address questions regarding the time course and persistency of these changes. For example, changes in lower extremity running and landing mechanics have been reported after a single session of instruction or video feedback.[13,29,30] The design of this study precludes the ability to discern the time course of changes in running mechanics among our participants during the 4-week training program. Based on the results of these previous studies it is possible that running mechanics changed very early in the training program and that 4 weeks of training is not necessary. Likewise, the persistency of the changes observed in this study is unknown. A future study with repeated assessment of running mechanics and a long-term follow up appears justified.

The presence of the investigator during motion analysis testing may have also influenced running mechanics. Subjects were not instructed to run differently during their follow-up motion analysis session. However, the authors did not include a placebo or control group that would mitigate this potentially confounding effect as well as clarify the influence of repeated testing, familiarity with the purpose of the study, and systematic differences in marker placement between visits. A future study with a control group that receives a placebo intervention program appears justified.

Delimitations of this study include the fact that all participants were healthy, highly motivated females who were compliant with the training program. As such, the generalizability of this study's findings to males and a diverse clinical population remains uncertain. It is also worth noting that the authors chose not to report differences in running mechanics that may have occurred over time in the transverse plane. Relative to frontal plane kinematics, skin motion artifact adds significant variability to transverse plane kinematic data.[31] As such, the authors chose not to include transverse plane variables, which also diminishes the possibility of type I error due to repeated statistical tests.

Despite uncertainty in the interpretation of the current results, the authors are encouraged by the fact that the participants in this study demonstrated systematic changes to hip and knee joint frontal plane running mechanics following a 4 week movement feedback program with a focus on visual, verbal, and tactile feedback of movement performance. This finding supports the possibility of changing running mechanics among individuals with altered movement patterns in a cost-effective manner.

CONCLUSION

Frontal plane hip and knee joint mechanics may contribute to running-related overuse injuries. As such, cost-effective interventions to improve these running mechanics are desirable. Participants in this study demonstrated decreased hip and knee abduction moments, increased knee adduction excursion, and decreased knee abduction excursion after a 4-week movement training program with a focus on verbal and visual feedback and manual neuromuscular facilitation techniques. Within the context of the limitations of this study, clinicians may consider these methods to improve running mechanics among females who demonstrate a medial knee position during a step down task.

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