



Original Article

Running gait biomechanics in female runners with sacroiliac joint pain

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Abstract. [Purpose] To identify running gait biomechanics associated with sacroiliac (SI) joint pain in female runners compared to healthy controls. [Participants and Methods] In this case-control study, treadmill running gait biomechanics of female runners diagnosed SI joint pain, (by ultrasound-guided diagnostic SI joint injection and/or ≥ 2 positive SI physical exam maneuvers) were compared with age, height, mass, and BMI matched healthy female runners. Sagittal and coronal plane treadmill running video angles were measured and compared. [Results] Eighteen female runners with SI pain, and 63 matched controls, were analyzed. There was no difference in age, height, mass, or BMI between groups. At the point of initial contact, runners with SI joint pain demonstrated less knee flexion, greater tibial overstride, and greater ankle dorsiflexion, compared to controls. In midstance, runners with SI pain had greater contralateral pelvic drop compared to controls. For unilateral SI joint pain cases (N=15), greater contralateral pelvic drop was observed when loading their affected side compared to the unaffected side. [Conclusion] Female runners with SI joint pain demonstrated greater contralateral pelvic drop during midstance phase; along with less knee flexion, greater “tibial overstride”, and greater ankle dorsiflexion at initial contact compared to controls.

Key words: Running, Female athlete, Sacroiliac joint pain

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INTRODUCTION

According to a recent report from the International Association of Athletics Federation, running's popularity has increased by nearly 60% over the past decade, with millions of people participating in running events annually, a trend largely fueled by a growing population of female runners, who now make up over 50% of race entrants¹). Despite the numerous health benefits of running²⁻⁶), musculoskeletal injuries are also common, with a 19–79% incidence among runners⁷⁻¹¹). Running-related injuries can be the result of overuse, anatomic predisposition, and/or problems with gait biomechanics¹²⁻¹⁴).

Injuries to the back, pelvis, hip, and thigh have been reported to account for approximately 25–35% of all injuries sustained by runners, and can require prolonged periods of rehabilitation and time away from sport¹⁵⁻¹⁸). Sacroiliac (SI) joint pain can be particularly challenging to diagnose and treat as therapeutic options are relatively limited^{19, 20}). Given that commonly used imaging modalities such as MRI and radiographs may show no abnormality in the setting of functional SI joint pain, diagnosis relies on detailed physical examination and the gold standard of diagnostic-anesthetic SI joint injections under ultrasound or fluoroscopic guidance^{21, 22}).

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The SI joint complex functions in the transmission, dampening, and distribution of forces from the lower extremities to the spine²³. Repetitive torsional and shear forces can cause deleterious effects, strain, and pain at the SI joint²⁴. Given the SI joint's integral role in force distribution during ambulation, return to sport can be especially challenging among runners and athletes participating in running-based sports, who repetitively load the lower extremities and lumbopelvic-hip girdle for prolonged periods of exercise and through varying degrees of fatigue which can alter an athlete's baseline gait biomechanics. Recent studies indicated that SI joint pain is more common among females than males, which has been posited to be in part due to gender-related differences in joint contour and orientation in relation to center of gravity, and hormonally-derived joint mobility, contributing to relatively less SI joint stability in females²⁵.

Running gait analysis has been utilized to evaluate patterns that are associated with several common running injuries²⁵⁻³⁰. Despite advances in a growing body of research on running gait mechanics and retraining, no published reports exist that have investigated running gait mechanics specifically in female runners with SI-joint pain. Identifying running mechanics associated with SI joint pain in a female population is the first step toward developing evidence-based strategies for the integration of running gait retraining into the management and prevention of SI joint pain in female runners.

The purpose of this study was to identify running biomechanical differences between healthy female runners and female runners with SI joint pain. We hypothesized that those with SI joint pain would exhibit poorer peri-pelvic control while running with coronal plane mechanics including greater contralateral hip drop (CPD), greater hip adduction, and greater knee valgus during midstance phase of the gait cycle compared to healthy controls. Additionally, we hypothesized that those with SI joint pain would demonstrate sagittal plane running mechanics at the point of initial contact (IC) that might contribute to a stiff landing and "breaking impulse" including less hip flexion, less knee flexion, greater "tibial overstride," and greater ankle dorsiflexion compared to healthy controls.

PARTICIPANTS AND METHODS

A case control retrospective study design was used. Video analysis of running treadmills is routinely obtained because it is a part of care included in clinical evaluation of patients in the Injured Runners Clinic at Boston Children's Hospital—Sports Medicine and the Micheli Center for Sports Injury Prevention. Two-dimensional video analysis was used with the intention that two-dimensional analysis is more commonly available in clinical facilities than three-dimensional motion capture, and thus findings would be more easily translated for wide clinical application. Institutional Review Board approval was obtained prior to commencement of this study.

All study participants signed informed consent for participation. The case group (N=18) included female patients seen at the Boston Children's Hospital Division of Sports Medicine (Boston, MA, USA), diagnosed with SI joint pain based on history and physical exam, including 2 or more positive SI joint pain provocative tests on physical exam and/or a positive response after ultrasound-guided SI joint injection of with rapid-acting anesthetic and corticosteroid (e.g. >90% pain relief on post-procedure SI-joint provocative testing). Physical exam testing criteria were established based on published data on the sensitivity and specificity of composite SI joint provocative physical exam test findings in the diagnosis of SI joint pain^{23, 31-34}. The control group (N=63) was comprised of asymptomatic female runners enrolled in the Running Injury Prevention Program at the Micheli Center for Injury Prevention (Waltham, MA, USA), matched based on age, height, weight, and BMI.

Inclusion criteria included female gender, self-identification as a runner or running-based sport participant. Exclusion criteria included: significant co-existing musculoskeletal pathology including history of orthopedic surgery for the back or lower extremity, significant congenital or acquired spinal pathology, neuromuscular disorders, rheumatologic conditions (e.g. spondyloarthropathies), or participant inability to tolerate treadmill running for 5 minutes for any reason including significant pain, medical comorbidity, or functional limitation.

Prior to initiating the video recordings, markers (neon-colored adhesive tape) were placed at key anatomic landmarks by a certified athletic trainer, including: the acromioclavicular joint of the shoulder, greater trochanter of the femur, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), medial and lateral femoral epicondyles, fibular head, fifth metatarsal head (the shoe overlying this bony landmark), distal achilles tendon, and the lateral malleoli.

All study participants had prior lifetime experience running on a treadmill. Prior to using the treadmill, participants did self-guided warm up stretching for 5 minutes. Each participant was instructed to "run at a comfortable pace they would choose if running a long distance" and subsequently selected their treadmill speed based on their comfort level. All participants maintained a pace of at least 4 miles per hour and demonstrated a flight phase in their gait cycle. Treadmill slope grade was set at zero. Each participant ran for a total of 5 minutes. Video recordings began after a minimum of 3 minutes of running and when the participant reported they had had adequate warm up and felt comfortable running at their preferred speed. Participants were asked to notify staff if they experienced any pain or discomfort while running.

Two high-speed video cameras (Casio Exlim 1, Casio, Ite, Tokyo, Japan), resolution 512 × 384 pixels at 300 frames per second (fps) were mounted on a commercially available casio video camera stand (Casio EX FH25, Casio America Inc., Dover, NJ, USA), locked at a standard height to maintain the video camera lens 84 centimeters from the floor with the camera mount apparatus locked in position to maintain the camera's orthogonal positioning relative to the floor. Videos were recorded using two separate cameras, for coronal plane and sagittal plane. The sagittal video (Fig. 1) camera stand was



Fig. 1. Overstride angle: generated by the intersection between a line drawn from the lateral malleolus to the fibular head, and a vertical line.

positioned at a distance of 2.5 meters from the center of the treadmill belt with the camera's optical axis perpendicular to the runner's plane of movement. The camera was confirmed to be in position in line with the runner's greater trochanter marker, for consistency. The posterior/coronal plane video camera was set up behind the treadmill (facing the dorsum of the runner) with the camera positioned 3 meters from the center point of the treadmill belt with the camera's optical axis in parallel with the runner's plane of movement. Coronal and sagittal plane videos included the runner's full body.

The video images were analyzed by blinded study personnel using ImageJ software (US National Institutes of Health; Bethesda, MD, USA). From the video recordings, 10–30 second video clips were created, with the goal of capturing 5 complete strides. Still-frame images were taken from the videos for measurement. For the purpose of this study ground reaction force (GRF) data from the Noraxon treadmill's force plate (Noraxon USA; Scottsdale, AZ, USA) was used strictly for correlation with video images and confirmation of key gait cycle events including initial contact, midstance, and toe off and delineation of stance and swing phases of the gait cycle. Initial contact (IC) event was identified as the first contact of the sole of the shoe with the treadmill on sagittal plane video, selected based on both visual review and confirmed by correlation with force plate recordings. Video of the coronal plane was assessed and midstance phase identified as the first sub-phase of single limb support when the full foot maintained contact with the ground while the contralateral leg was moving through swing phase. Midstance phase on coronal video was confirmed by correlation with vertical GRF apex before conversion into terminal stance phase. Each still-frame image selected for analysis was taken after at least the third foot strike on the clip, in order to allow the study personnel analyzing the video to familiarize with the participant's gait pattern and most accurately select the video still-frame image reflecting the gait cycle event of interest.

SI Joint Pain Provocative Physical Exam Tests used in the diagnosis of SI joint pain outlined below have been described previously in the literature, with 2 or more positive tests combined demonstrated to have excellent sensitivity and specificity^{31–34}).

POSITIVE TEST: Pain reproduced at the SI joint.

- **SI Compression Test:** With patient in decubitus position, a vertically directed force is applied to the iliac crest directed towards the floor, transversely across the pelvis, compressing the SI joints.

- **SI Thigh Thrust Test:** With the patient in supine position with the affected-side hip in 90 degrees flexion, the sacrum is fixated against the table with the examiner's hand, and a vertically oriented force is applied through the line of the femur directed posteriorly, producing a posterior shearing force at the SI joint.

- **Sacral Thrust Test:** With patient in prone position, a vertically directed force is applied to the midline of the sacrum at the apex of the curve of the sacrum, directed anteriorly, producing a posterior shearing force at the SI joints with the sacrum nutated.

- **Gaenslen's Test:** With the patient in supine position, one hip in 90 degrees of flexion and the contralateral hip in 0–5 degrees extension off the edge of the exam table, the pelvis is stressed with a torsion force by a superior/posterior force applied to the knee and a posteriorly directed force applied to the contralateral knee.

- **SI Distraction Test:** With the patient in supine position, vertically oriented pressure is applied to the anterior superior iliac spinous processes directed posteriorly, distracting the sacroiliac joint.

- **Patrick's FABER Test:** With the patient in supine position, the affected side leg is held in flexion, abduction, and external rotation, with the affected-side foot crossed over the opposite-side thigh. The pelvis is stabilized at the opposite ASIS with the hand of the examiner. A gentle downward force is applied to the affected-side knee of the patient and is steadily increased, exaggerating the motion of hip flexion, abduction, and external rotation.

- **Sacral Torque Test:** With patient in decubitus position, a horizontally directed force is applied to the sacrum while a torque rotation force is generated by the examiner's top hand applying posterior rotational force to the anterior iliac spine.

SAGITTAL PLANE ANGLES: Measured from still-frame images extracted from video taken from video camera positioned to the runner's side (sagittal plane). Measurements are based on anatomic landmarks identified and marked on the limb ipsilateral to the location of the camera at the point of initial contact.

- **Trunk Posture Angle:** Generated by the intersection between a line from the superior tip of the greater trochanter to the acromioclavicular joint and a vertical axis (angle measurements anterior to the greater trochanter denoted as positive, and angle measurements posterior to the greater trochanter were denoted as negative).
- **Pelvic Tilt Angle:** Generated by the intersection between a line drawn from the Anterior Superior Iliac Spine (ASIS) to the Posterior Superior Iliac Spine (PSIS) and level horizontal axis.
- **Hip Flexion Angle:** Generated by the intersection between a line drawn from the greater trochanter to the center of the knee and a vertical axis.
- **Knee Angle:** Generated by the intersection of a line drawn from the greater trochanter to the center of the knee, and a line from the center of the knee to the lateral malleolus.
- **Overstride Angle:** Generated by the intersection between a line drawn from the lateral malleolus to the fibular head, and a vertical line. Angle measurement anterior to the fibular head are considered positive and those posterior to the fibular head are considered negative angles.
- **Ankle Angle:** Generated by the intersection of a line drawn from the fibular head to the lateral malleolus, and a line from the lateral malleolus to a marker on the shoe overlying the fifth metatarsal head.
- **Foot Inclination Angle:** Generated by the intersection between a line drawn along the sole of the shoe and the treadmill surface.

CORONAL PLANE ANGLES: Measured from still-frame images extracted from footage taken from video camera positioned posterior to the runner. Angles are ascribed to the weight bearing limb in midstance of the running gait cycle.

- **Contralateral Pelvic Drop Angle:** Generated by the intersection of a line drawn between the PSIS of the weight bearing limb and the PSIS of the contralateral side, and a horizontal axis. Angle is ascribed to the weight bearing limb.
- **Hip Adduction Angle:** Generated by the intersection of a line drawn between the greater trochanter of the femur and the midline of the posterior knee (point equidistant between the medial and lateral femoral condyles), and a vertical axis.
- **Knee Valgus Angle:** Generated by the intersection of a line drawn between the greater trochanter of the femur and the midline of the posterior knee (point equidistant between the medial and lateral femoral condyles), and a line from the midline of the posterior knee to the distal insertion of the Achilles.

For statistical analysis: for continuous variables, Shapiro-Wilk test was used to determine normality of distribution. When the normality was not violated, independent t-test was used. Conversely, when the data were not normally distributed, Mann-Whitney U test was employed. Physical characteristics including age, height, mass, and BMI were compared between runners with SI joint pain and healthy controls. Biomechanical variables of interest analyzed included sagittal plane angles at point of initial contact: trunk posture angles, pelvic tilt angles, hip flexion angles, knee flexion angles, tibial overstride angles, ankle dorsiflexion angles, and foot inclination angles, along with coronal plane angles at midstance: contralateral pelvic drop (CPD), hip adduction angle, and knee valgus angle. For categorical variables, foot strike type at IC in sagittal plane, a χ^2 analysis was used for right and left foot separately. The foot strike was originally categorized rearfoot and non-rear foot strike types. Then, the foot strike patterns were further compared by proportion of rearfoot, midfoot, and forefoot strikes. For all comparisons, $p=0.05$ was used as a critical statistical significant value, and the IBM SPSS statistical software (Version 23, SPSS Inc, Chicago, IL, USA) was used for all analyses.

RESULTS

A total of 81 runners met the inclusion criteria (runners with SI pain: $N=18$, healthy control runners: $N=63$). Because the Shapiro–Wilk test indicated non-normally distributed patterns in continuous variables, Mann–Whitney U test was used. There were no differences in age, height, mass, and BMI between the two groups (Table 1).

In the sagittal plane at IC, runners with SI pain had significantly less knee flexion ($p=0.018$) and greater tibial overstride angles ($p=0.026$). Those with SI pain also demonstrated greater ankle dorsiflexion ($p=0.010$) and foot inclination angles at the point of IC ($p<0.001$) (Table 2). There was no significant difference in sagittal plane IC hip angles, pelvic tilt angles, and trunk posture angles (Table 2).

Table 1. Descriptive characteristics of runners with and without sacroiliac (SI) joint pain

	Runners without SI pain (N=63)	Runners with SI pain (N=18)
Age (years)	27.3 ± 12.9	23.8 ± 10.5
Height (cm)	167.6 ± 11.1	168.3 ± 9.3
Mass (kg)	61.0 ± 12.9	62.1 ± 6.8
BMI (kg/m ²)	21.6 ± 3.4	21.6 ± 1.4

SI: sacroiliac; BMI: body mass index.

In the coronal plane at midstance phase, for runners with SI pain- when their symptomatic side was weightbearing, there was significantly greater CPD compared to healthy controls ($p=0.005$) (Table 3). There was no significant difference identified in hip adduction angles or knee valgus angles between runners with SI pain and healthy controls (Table 3).

For foot strike pattern categories (rearfoot, midfoot, and forefoot strike), 87% of all runners in the study exhibited a rearfoot strike pattern. A χ^2 analysis did not indicate any statistical difference in categorical footstrike patterns between limbs with SI pain and healthy controls (Table 4).

DISCUSSION

Female runners with SI joint pain demonstrated significant differences in certain components of running gait mechanics compared to controls. In the sagittal plan at IC, those with SI joint pain demonstrated what has been characterized as “braking impulse mechanics” with less knee flexion, greater “tibial overstride”, and greater ankle dorsiflexion, when compared to these measures in healthy controls—effectively creating a landing mechanism that is stiffer and lands the foot farther in front of the runner’s center of mass. In coronal plane at midstance, when the affected limb was weightbearing, there was significantly greater CPD compared to healthy control runners. Moreover, for patients with unilateral SI joint pain ($N=15$), a significantly higher degree of CPD was seen on the symptomatic side compared to degree of CPD for the asymptomatic limb, suggestive of poorer hip control on the symptomatic side. Among healthy controls there was no significant difference in CPD between their right and left lower extremities.

The SI joints play a key role in both dampening and distributing GRF during ambulation^{16, 35, 36}. The SI joint surfaces are positioned in parallel to vertical loading forces, making the joint vulnerable to shear forces^{37–39}. Although multiple there are multiple stabilizing mechanisms for the joint, including gross orientation, intraarticular surface contour, and compression by overlying ligaments and fascia, when stressed, SI joint motion can occur along multiple axes, including rotation up to 8 degrees and translation up to 8 mm^{38–43}.

Our findings supported our hypothesis that runners with SI joint pain would demonstrate a “stiff” landing with less knee flexion, greater tibial overstride, and greater ankle dorsiflexion at the point of IC. Previous studies have demonstrated associations between greater tibial overstride angles with relatively high GRF in running^{44–47}. Overstride patterns and higher magnitude GRF has been found to be associated with running-related musculoskeletal injuries such as stress fractures in the

Table 2. Sagittal plane running mechanics angles at initial contact

	Runners without SI pain (N=63)	Runners with SI pain (N=18)
Trunk posture angle (degrees)	4.1 ± 2.8	3.6 ± 1.6
Pelvic tilt angle (degrees)	12.9 ± 6.8	13.5 ± 5.4
Hip flexion angle (degrees)	153.9 ± 6.6	154.9 ± 7.2
Knee flexion angle (degrees)	163.7 ± 6.5	169.3 ± 3.4*
Tibial overstride angle (degrees)	6.4 ± 4.4	10.0 ± 2.2*
Ankle angle (degrees)	85.9 ± 7.4	78.9 ± 2.8**
Foot inclination angle (degrees)	9.2 ± 4.5	18.3 ± 4.5***

SI: sacroiliac. * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 3. Coronal plane running mechanics at midstance phase

	Runners without SI pain (N=63)	Runners with SI pain (N=18)
Contralateral pelvic drop angle (degrees)	5.22 ± 2.6	7.8 ± 3.8**
Hip adduction angle (degrees)	7.5 ± 2.4	8.01 ± 1.7
Knee valgus angle (degrees)	176.3 ± 2.2	176.27 ± 2.1

SI: sacroiliac. ** $p<0.01$.

Table 4. Foot strike pattern categorization in limbs with sacroiliac (SI) pain and asymptomatic limbs

	Limbs without SI pain (N=144)	Limbs with SI pain (N=18)
Rearfoot	124 (86%)	18 (100%)
Midfoot	8 (5.5%)	0
Forefoot	12 (8.3%)	0

SI: sacroiliac.

lower leg and plantar fasciitis^{9, 10, 48-50}). When the knee flexes from the point of IC through loading phase, there is eccentric contraction of the quadriceps, helping to absorb GRF⁴⁴). Those who land with a less flexed knee have a “stiffer” landing, with less engagement of the quadriceps muscles in the loading phase and potentially leading to greater force vectors being transmitted up the kinetic chain to the SI joint. Several studies have synthesized the mechanical implications of ankle dorsiflexion on GRF load and distribution in the lower extremities^{21, 36, 50, 51}). Kinematic and kinetic running analyses by Tam et al. demonstrated a positive association between increased ankle dorsiflexion at IC and initial force loading rate in runners⁵²). Loading rate has been found to be a risk factor for tibial stress fractures and other running-related injuries^{53, 54}). Increased loading rates experienced by runners in a greater degree of ankle dorsiflexion at IC could contribute to stress on the SI joint. Lieberman et al. analyzed the kinetic influence of ankle dorsiflexion at IC, demonstrating that a highly dorsiflexed ankle will convert little translational energy into rotational energy about the ankle joint, increasing the magnitude of the impact transients³⁶). Moreover, the degree of ankle dorsiflexion at IC alters the way that runners attenuate the rate of loading, and the more dorsiflexion at IC, the less effective soft tissue involvement in force distribution^{50, 52}).

In addition to these mechanical factors, there were significant differences between coronal plane mechanics in runners with SI pain compared to those without. When a symptomatic limb with SI pain was loaded through midstance phase, there was significantly greater CPD. Ireland et al found that weakness of the hip abductors causes increased coronal plane hip motion⁵⁵). Abnormal motor control patterns of the gluteus medius are found in individuals with low back pain⁵⁶). When the limb is loaded, dysfunction of the hip abductors leads to contralateral pelvic drop, hip internal rotation, and valgus force at the knee. In order to maintain balance, there may be compensatory rotation of the pelvis into a counternutated position, with ventral rotation of the iliac bones relative to the sacrum and predisposing the SI joint to strain and pain. Vleeming et al. showed that the long dorsal SI ligament is tensed when counternutated (dorsal rotation of the sacrum relative to the iliac bones with movement of the sacral promontory posteriorly and superiorly with concurrent ventral ilium-on-sacrum rotation) and slackened when the SI joints are nutated (ventral rotation of the sacrum relative to the iliac bones with movement of the sacral promontory anteriorly and inferiorly with concurrent dorsal ilium-on-sacrum rotation. Nutation likely leads to more effective compression and force closure of the SI joint^{42, 43, 57, 58}). Hungerford et al. showed that fully reversed movement patterns between healthy individuals and SI joint pain patients, where nutation was found to occur in healthy persons on the weightbearing side, but counternutation was found to occur on the weightbearing side in those with SI joint pain dysfunction. These findings are thought to be due to reduced tonicity of the erector spinae, gluteus maximus, biceps femoris, and external oblique muscles⁵⁹). This type of inappropriate postural loading may have marked effects on stresses on the SI joint^{60, 61}).

There were limitations to this study that warrant consideration. First, two-dimensional video technology was utilized, limiting our ability to collect data on horizontal plane (Z-axis) motion as would be captured with three-dimensional technology. That being said, findings in this study may be more broadly clinically applicable given that two-dimensional gait evaluation technology is far more commonly available in most clinical settings. Additionally, it is known that soft tissue artifact is inherent in surface-based movement analysis, and can be a significant source of error in movement analysis in humans. However, it is expected that this error is systematically applied and does not bias between-group comparisons. However, considering the relatively small difference between groups for these coronal and sagittal plane variables, results should be interpreted with acknowledgement of these factors^{62, 63}). Whereas this study focused on treadmill-based running, further research is needed to verify the biomechanical features identified in this study also apply in the setting of over ground running⁶⁴). Further research is. Although this study provides an important first step in the identification of biomechanical features associated with SI joint pain in runners, future prospective longitudinal studies will further inform sports medicine professionals and coaches to help mitigate risk of this this running-related injury.

This study was designed to identify running mechanical features associated with SI joint pain in a population of female runners. Female runners with SI joint pain demonstrated sagittal plane mechanics with significantly “stiffer landing” including less knee flexion, greater tibial overstride, and greater ankle dorsiflexion at the point of initial contact. In the coronal plane, those with SI pain had a greater degree of contralateral pelvic drop during midstance phase, suggestive of altered lumbosacral and hip abductor muscle recruitment for those with SI pain. While further studies are warranted, these findings suggest a potential role for gait analysis and retraining in the management of SI joint pain, a common running-related injury.

Author contributions

All of the named authors contributed to study design, data collection and interpretation, and approved the final manuscript as submitted.

Conflicts of interest

All authors have no conflict of interest to disclose.

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