Original Research

Movement Variability and Loading Characteristics in Athletes With Athletic Groin Pain

Changes After Successful Return to Play and Compared With Uninjured Athletes

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Background: Athletic groin pain (AGP) can lead to altered movement patterns during rapid deceleration and acceleration. However, the effect of AGP on movement variability and loading patterns during such actions remains less clear.

Purpose: To investigate, using a continuous lateral hurdle hop task, how movement variability and magnitude measures of 3-dimensional (3D) kinematic, kinetic, and vertical ground-reaction force (vGRF) variables are (1) affected by AGP (AGP vs uninjured controls [CON]) and (2) changed after successful rehabilitation (AGP prerehabilitation vs AGP postrehabilitation vs CON).

Study Design: Controlled laboratory study.

Methods: A total of 36 athletes diagnosed with AGP and 36 uninjured CON athletes matched on age (18-35 years), level (subelite), and type of sports played (multidirectional field sport) performed a continuous lateral hurdle hop test that involved 10 side-to-side hops over a 15-cm hurdle. The 3D joint kinematic, kinetic, and vGRF variables (total, eccentric, and concentric; ground contact time, peak force, and impulse; and eccentric rate of force development) were examined. The AGP and CON groups were tested at baseline, and the AGP group was retested after participants successfully completed a standardized, exercise-based rehabilitation program targeting intersegmental control.

Results: There were no differences in baseline characteristics between the AGP (mean ± SD: age, 27.5 ± 4.8 years; height, 179.8 ± 6.3 cm; mass, 80.3 ± 7.1 kg) and CON (mean ± SD: age, 24.1 ± 4.5 years; height, 181.0 ± 5.8 cm; mass, 80.4 ± 8.2 kg) groups. At baseline, athletes with AGP demonstrated altered loading patterns in the vGRF (longer ground contact times, reduced peak force, and reduced rate of force development) compared with CON athletes, while no significant difference in any movement variability variables was evident. After rehabilitation, the athletes with AGP demonstrated significant changes in transverse and coronal plane hip and trunk kinematics, with no significant differences in vGRF variables compared with the CON group.

Conclusion: The differences in baseline vGRF measures between the AGP and CON groups were no longer evident after athletes with AGP underwent rehabilitation. No differences in movement variability were evident between the AGP and CON groups, either before or after rehabilitation.

Clinical Relevance: Rehabilitation programs should consider targeting intersegmental hip and trunk movement patterns to positively influence loading patterns in athletes with AGP.

Keywords: rehabilitation; biomechanics; hip pain, groin pain

Athletic groin pain (AGP) is a common overuse musculoskeletal condition prevalent in many field-based sports that involve repetitive change of direction, jumping, landing, and sprinting actions.[45,47,48] Clinical diagnosis encompasses multiple pathologies of the myotendinous and fascial structures that attach to the pubic symphysis, which are all located in close proximity to one another.[19,32,63] It has been suggested that insufficiencies in segmental movement control (eg, between the trunk and pelvis) during sporting actions can influence the distribution of mechanical forces across the pubic symphysis, resulting in excessive, repetitive loading to specific structures and the propagation of AGP.[23]

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A number of recent studies have investigated joint kinematics and kinetics to better understand the injury mechanism(s) of AGP.[18,25,26,35,37,52,55] For example, Gore et al[26] investigated the effects of AGP and successful rehabilitation on whole-body kinematics and kinetics during a lateral hurdle hop task. These authors found that 18 variables significantly differed between the AGP and control groups when compared with prerehabilitation, and 7 of these variables were no longer significantly different in the AGP group after successfully completing a rehabilitation program focused on improving intersegmental movement control.[26,37] However, these authors did not examine movement variability or loading characteristics (ie, peak force, rate of force development [RFD], and impulse) of the vertical ground-reaction force (vGRF), and given the association between repetitive loading and overuse injuries,[2,60] further examination of these factors with respect to AGP is warranted.

Movement variability has been described as the natural variations across multiple repetitions of the same task.[5] It is theorized to play a functional role in tissue health by altering the magnitude, location, and/or direction of loads placed on the body to minimize injury risk caused by repetitive loading.[29,30] In a recent systematic review, Baida et al[2] found that deviations away from normal ranges of variability (both greater and reduced variability) may be associated with lower limb overuse injury. Only 2 previous studies have examined movement variability in relation to AGP, with conflicting findings reported with both increased and decreased movement variability in athletes with AGP compared with uninjured controls.[18,40] Edwards et al[18] found both increased and decreased joint motion variability in athletes with a history of AGP at discrete time points (eg, initial contact) of a running cut task when compared with uninjured control athletes, while Mansourizadeh et al[40] found increased variability in intersegmental coordination between thigh-pelvis-thoracic segments during a change of direction walking task. During walking tasks or field-based sports, athletic performance is rarely based on the athlete's ability to perform a single discrete movement but rather on his or her ability to produce continuous explosive movements for effective performance.[21] Therefore, variability may be better examined during a continuous explosive movement task, as it promotes the natural variation in movement patterns while an individual continually adjusts one's action between trials of the task.[28]

GRF, which represents the summated measure of impact forces exerted on the body's segments, is an important measure of loading on the body. The vGRF has frequently been investigated as a potential risk factor for lower limb injuries from overuse, using peak, rate of loading, and impulse measures.[36,60,62] To date, only 2 studies have examined the GRF in AGP, with different movement tasks examined and conflicting findings reported.[18,26] Gore et al[26] reported significantly reduced vGRF (effect size $d = 0.73$) in athletes with AGP when compared with uninjured control athletes during the stance phase of a lateral hurdle hop task. In contrast, Edwards et al[18] reported greater peak vGRF in athletes with AGP when compared with uninjured control athletes during the weight acceptance phase of an unanticipated cutting task. In addition to these conflicting findings, no study has examined how AGP affects the rate of loading or impulse of the vGRF, and it has been suggested that these measures may be of greater importance than peak force measures as they provide greater insight into the levels of strain placed on tissues.[54]

The aims of this study were to investigate how movement variability and magnitude measures of 3-dimensional (3D) kinematic, kinetic, and vGRF variables were (1) affected by AGP (AGP vs uninjured controls [CON]) and (2) changed after successful rehabilitation in athletes with AGP (AGP prerehabilitation vs AGP postrehabilitation vs CON) when examined during a continuous lateral hurdle hop task. We hypothesized that the athletes with AGP would demonstrate increased movement variability and reduced vGRF loading compared with the CON athletes and that these differences would normalize in the APG athletes postrehabilitation.

METHODS

Study Design and Setting

This study was designed as a cohort study with a pre- to postintervention analysis. The study was conducted in the Sports Medicine Department, Sports Surgery Clinic. Enrollment started in June 2018 and ended in October 2019. The data taken for this investigation were part of a larger intervention study (Baida et al[3]). Using previous Copenhagen Hip and Groin Outcome Score (HAGOS) data,[37] with 80% power and an alpha error probability of .05, we calculated a priori that 36 participants were required. Ethical approval for the study protocol was

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Ethical approval for this study was obtained from the Sports Surgery Clinic.

granted by our institution, and all study participants provided informed consent.

Participants

Included in this study were 36 athletes (mean ± SD: age, 27.5 ± 4.8 years; height, 179.8 ± 6.3 cm; mass, 80.3 ± 7.1 kg) who attended our clinic and were diagnosed with AGP. In addition, 36 uninjured control athletes (mean ± SD: age, 24.1 ± 4.5 years; height, 181.0 ± 5.8 cm; mass, 80.4 ± 8.2 kg) were included. AGP participants were included if they (1) had an anatomic diagnosis falling under AGP (iliopsoas, adductor, pubic aponeurosis, inguinal, and hip),[20] (2) were a man aged between 18 and 35 years involved in multidirectional field-based sports, (3) had hip/groin symptoms during sporting activity with a duration longer than 4 weeks,[37] and (4) planned to return to the same preinjury sport and level of competition. Exclusion criteria included (1) hip joint arthrosis (grade $\geq$3 on magnetic resonance imaging [MRI]), (2) those with an underlying medical condition (eg, inflammatory arthropathy or infection), and (3) a history of hip/groin surgery.

Diagnosis of AGP was made by a sports and exercise medicine physician (A.F.-M.) and included MRI review as well as clinical examination;[19] including hip range of motion tests; hip provocation tests; bilateral adductor squeeze test; crossover test; slump and femoral slump test; and palpation of the adductor insertion to the tubercle, pubic symphysis, and superficial and deep inguinal ring scrotal invagination. Diagnoses falling under the umbrella term AGP were recorded as pubic aponeurosis injury, adductor longus injury, hip injury, hip flexor injury, and/or inguinal injury (for full details of the clinical examination and diagnoses of AGP, the reader is directed to Falvey et al[19]). Control participants were included if they had (1) no previous groin or lower limb surgery and (2) no lower limb injury within the previous 3 months. Control participants were recruited via social media outlets and local sporting clubs and were matched based on age profile (18-35 years), sports played (multidirectional field-based sports), and level of competition (subelite). Gaelic Athletic Association sports (football and hurling) were the most common sports played in the AGP group (72%) and CON group (73%), followed by soccer (AGP, 25%; CON, 17%). In the AGP group, the most common anatomic diagnoses were pain or tenderness at the pubic aponeurosis (61%), followed by proximal adductor tendon insertion (17%), iliopsoas (14%), hip (6%), and inguinal (3%).

Intervention

A rehabilitation program focusing on intersegmental control through strength, linear running, and change of direction mechanics was employed and prescribed by 2 authors (S.B. and E.K.). The content and criteria for progression through the program have been published previously[3,37] and are available separately as Supplemental Material. In brief, the program consists of 3 levels, with each level designed to address a specific component of recovery (ie, level 1, strength; level 2, linear running movements; and level 3, change of direction movements). Progression between the 3 levels of rehabilitation is individualized, based on the achievement of clinical milestones. These clinical milestones are assessed by the treating physical therapist and must be achieved before an athlete is cleared to return to play; they include symmetrical hip flexion and internal rotation range of motion, as well as pain-free completion of the squeeze tests in 45° and 0° of hip flexion,[13] Thomas test,[31] and running programs. No adjunctive treatments (eg, soft tissue massage and therapeutic ultrasound), oral medication (eg, nonsteroidal anti-inflammatories), and/or injections were given to the athletes in the AGP group.

Testing Procedure

The AGP prerehabilitation group (AGP–Pre) and the CON group attended the clinic for baseline testing, and the AGP group repeated the testing at return to play after successfully completing the rehabilitation program (AGP–Post). All athletes undertook a standardized warm-up before their biomechanical test session.[43] The continuous lateral hurdle hop test involved athletes performing 10 continuous side-to-side hops, on a dual force plate system, over a 15-cm hurdle (see Video Supplement). From a stationary start, athletes were instructed to perform the hops as quickly as possible, with hands unrestricted, and no time limit for task completion was set. The nonsymptomatic (AGP) or dominant (CON) limb was tested first, and the initiating hop was in a lateral direction, immediately followed by a medial hop and so forth until completion (eg, if the left leg was reported as the nonsymptomatic/dominant side, then the initial hop was over the hurdle to the left and vice versa). Each athlete performed 1 warm-up trial before the maximum effort trial was undertaken. If an athlete failed to complete the 10 continuous hops (eg, stumbled or double hopped), a second trial was performed. If, after the second trial, an athlete was still unable to complete 10 continuous hops, the trial with the highest number of continuous hops was included for analysis. A 2-minute rest period was given between each trial.

Self-reported disability and function were assessed at baseline (CON and AGP–Pre groups) and at return to play after rehabilitation (AGP–Post group) using the HAGOS (range, 0-100, with 100 indicating no problems),[58] and the level of sporting activity was assessed with the Marx activity scale[33] (range, 0-16, with higher scores indicating increased frequency of high-demand sporting activity).

Data Processing

Reflective markers (14-mm diameter) were placed on bony landmarks on the lower limbs, pelvis, and trunk as per the Vicon Plug in Gait model (Vicon Motion Systems), synchronized with two 40 × 60–cm force platforms (BP400600; AMTI) collecting GRF data. Motion and force data were captured at a sampling frequency of 200 Hz and 1000 Hz, respectively. Both marker and force data were filtered using a fourth-order Butterworth filter with a cutoff frequency of 15 Hz.[38] Kinematic and kinetic calculations were performed in Nexus software (Vicon Motion Systems). The vGRF was normalized to body mass, and the following variables were calculated: total, eccentric, and concentric; ground contact time (GCT), peak force, and impulse; and eccentric RFD. The eccentric phase was defined from initial ground contact to zero center of mass power, and the concentric phase was defined from zero center of mass power to the toe-off.

Each participant was screened for outliers. First, GCTs that were too long or too short were identified (ie, represented a stumble, double hop, or regaining balance) and removed using the Dixon *Q* test.[12] Second, the GRF waveforms and motion capture data were manually screened to identify adverse events (eg, stumble and double hop). When an adverse event was identified, this hop and the subsequent hop were excluded from the biomechanical analysis, thereby ensuring only representative continuous hops were statistically examined. After the screening process, the first 6 continuous lateral hops from each trial were included for analysis; when this was not possible (ie, during adverse events), 6 consecutive hops were included (eg, hops 4-10) or hops either side of an adverse event (eg, hops 1-3 and 7-10). Six hops has previously been shown as the optimal number of trials required to provide a representative mean during a lateral hurdle hop task.[27]

Statistical Analysis

Descriptive statistics for the kinematic, kinetic, and vGRF data were calculated using MATLAB (Version R2015a; The MathWorks), and data visualization was conducted using R statistical software (Version 3.6.2). Normality was assessed (Shapiro-Wilk test) and parametric statistics applied. The magnitude of movement variability was determined using the SD (1) at each time point across the biomechanical waveform for the kinematic and kinetic data over the 6 trials, and (2) for each vGRF variable over the 6 trials. Statistical parametric mapping was used to identify differences in kinematic and kinetic measures between the groups (AGP–Pre vs CON, AGP–Post vs CON, AGP–Pre vs AGP–Post).[50] For vGRF data, unpaired *t* tests (AGP–Pre vs CON, AGP–Post vs CON) and paired *t* tests (AGP–Pre vs AGP–Post) were utilized. The alpha level for all tests was set at .05. The Cohen effect size (*d*) was reported as small (<0.5), medium (0.5-0.8), and large (>0.8).[9] For nonparametric tests, effect sizes (*r*) were calculated by dividing the *z* value by $\sqrt{n}$ (where *n* is the sample size), with thresholds of small (<0.1), medium (0.1-0.4), and large (>0.5) effect sizes.[49]

To improve the generalizability of the findings (ie, by increasing the number of samples tested) and reduce random sampling bias, a permutation analysis was applied.[8] Thirty CON and AGP participants were randomly selected from the data. This number was chosen to ensure that the central limit theorem could be assumed (ie, $n \geq 30$). The CON group was then randomly matched with the AGP group for leg dominance (preferred kicking leg) and statistically compared with the AGP group, both at baseline and after AGP rehabilitation. This randomization process was completed 100 times, findings were aggregated to their mean values (*P* values and effect sizes), and only statistically significant findings that were identified in ≥85% of the random samples were considered true differences.

TABLE 1
Baseline Participant Characteristics, Sports Played, and Clinical Diagnoses[a]

	AGP–Pre (n = 36)	CON (n = 36)	*P*
Age, y	25.9 ± 4.9	24.1 ± 4.5	.169
Height, cm	179.7 ± 6.5	181.0 ± 5.8	.408
Mass, kg	80.3 ± 7.2	80.4 ± 8.2	.938
Sports played, %			
GAA football	58	67	—
Soccer	25	17	—
GAA hurling	14	6	—
Rugby	3	8	—
Basketball	0	3	—
Symptom duration, wk	38.7 ± 5.5	—	—
Primary diagnosis, n (%)			
PA	22 (61)	—	—
AL	6 (17)	—	—
Psoas	5 (14)	—	—
Hip	2 (6)	—	—
Inguinal	1 (3)	—	—

[a] Data are reported as mean ± SD unless otherwise indicated. Dashes indicate not applicable. AGP–Pre, athletic groin pain group before rehabilitation (baseline); AL, adductor longus related pain; CON, uninjured control group; GAA, Gaelic Athletic Association; PA, pubic aponeurosis related pain.

RESULTS

After attending the clinic a mean of 4.7 ± 1.3 times for individual physical therapy appointments, 36 athletes with AGP returned to play at a mean time of 9.8 ± 3.0 weeks. Table 1 presents baseline participant characteristics between the AGP–Pre and CON groups. There were no significant differences between the groups in age, height, or weight.

At baseline testing, all HAGOS subscale scores ($P < .001$; $r = -0.74$ to -0.89) and Marx scores ($P < .001$; $r = -0.70$) were significantly lower in the AGP–Pre group when compared with the CON group (Table 2). At return-to-play testing, all HAGOS subscale scores ($P < .001$; $r = -0.50$ to -0.60) and Marx scores ($P = .002$; $r = -0.42$) improved significantly with large effect sizes in the AGP–Post athletes, although these scores remained significantly less when compared with the CON group, with the exception of HAGOS Symptoms, which was not significantly different between the AGP–Post and CON groups (Table 2).

Comparison of 3D Kinematic, Kinetic, and Vertical GRF Variables

AGP–Pre Versus CON. At baseline testing, significant differences of small to moderate effect size were observed in 3 of the vGRF variables when comparing the AGP–Pre with the CON group. The AGP–Pre group displayed significantly greater GCT ($P = .025$; $d = 0.43$) and concentric impulse

TABLE 2
Patient-Reported Outcome Scores in the AGP–Pre, AGP–Post, and CON Groups[a]

				AGP–Pre vs CON		AGP–Pre vs AGP–Post		AGP–Post vs CON	
Measure	CON	AGP–Pre	AGP–Post	*P*	*r*[b]	*P*	*r*[b]	*P*	*r*[b]
HAGOS									
Symptoms	89.3 (84.8-97.3)	60.2 (56.3-75.0)[c]	83.9 (75.0-92.9)[d]	**<.001**	–0.74	**<.001**	–0.58	.112	–0.27
Pain	97.5 (94.4-100.0)	76.3 (63.1-85.6)[c]	92.5 (85.0-97.5)[d,e]	**<.001**	–0.76	**<.001**	–0.53	**.020**	–0.40
ADL	100.0 (98.8-100.0)	75.0 (70.0-90.0)[c]	95.0 (88.8-100.0)[d,e]	**<.001**	–0.76	**<.001**	–0.50	**.014**	–0.41
Sport Rec	98.4 (93.9-100.0)	54.7 (39.9-67.2)[c]	85.9 (80.5-93.8)[d,e]	**<.001**	–0.82	**<.001**	–0.60	**.002**	–0.48
PA	100.0 (100.0-100.0)	6.3 (0.0-37.5)[c]	50.0 (21.9-75.0)[d,e]	**<.001**	–0.89	**<.001**	–0.52	**<.001**	–0.77
QOL	100.0 (90.0-100.0)	35.0 (30.0-45.0)[c]	67.5 (45.0-80.0)[d,e]	**<.001**	–0.83	**<.001**	–0.56	**<.001**	–0.69
Marx	16.0 (13.8-16.0)	4.0 (0.0-8.3)[c]	12.0 (9.0-12.0)[d,e]	**<.001**	–0.70	**.002**	–0.42	**<.001**	–0.61

[a] Scores are reported as median (interquartile range). Boldface *P* values indicate a statistically significant difference between groups ($P < .05$). ADL, Activities of Daily Living; AGP, athletic groin pain; CON, uninjured control group; HAGOS, Hip and Groin Outcome Score; PA, Participation in Physical Activity; Post, after rehabilitation; Pre, before rehabilitation (baseline); QOL, Quality of Life; Sport Rec, Sport and Recreational Activities.

[b] r = effect size (small, <0.1; medium, 0.1-0.5; large, >0.5).

[c] AGP–Pre < CON ($P < .001$).

[d] AGP–Pre < AGP–Post ($P < .001$).

[e] AGP–Post < CON ($P < .05$).

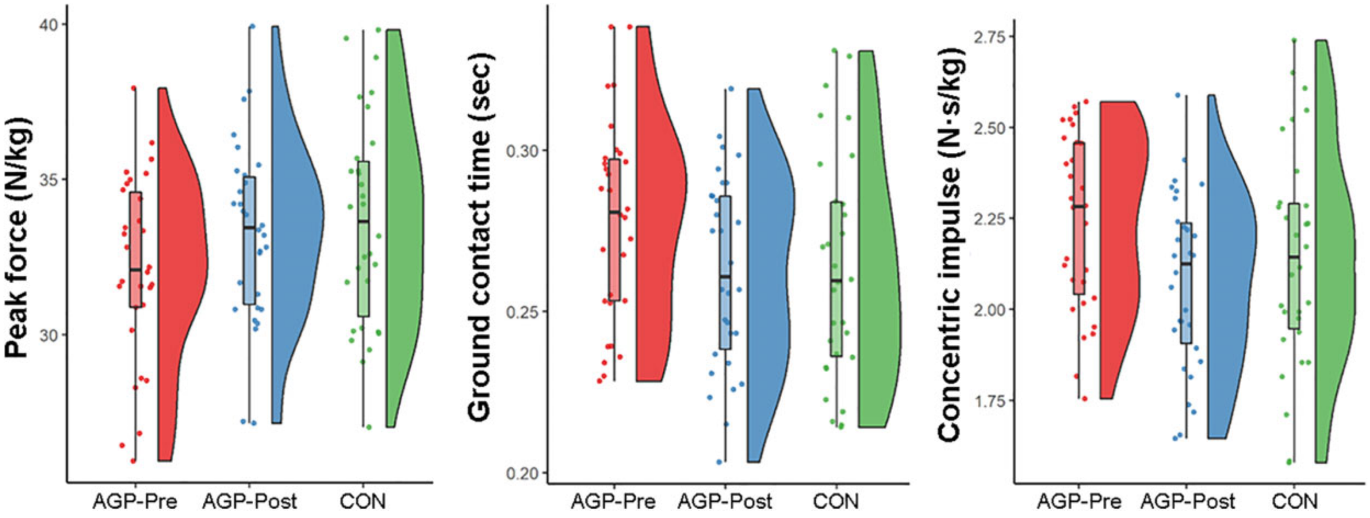

Figure 1. Box plots with violin charts of the vertical ground-reaction force variables that were significantly different between the athletic groin pain (AGP) and control (CON) groups at baseline testing. Post, postrehabilitation (return-to-play testing); Pre, prerehabilitation (baseline testing). Note these figures represent one of the random sample sets taken during the permutation analysis.

($P = .028$; $d = 0.52$) compared with the CON group, and significantly less peak vGRF ($P = .025$; $d = 0.36$) (Figure 1). In 2 other vGRF variables, a trend toward significance was observed with reduced eccentric peak force ($P = .029$; $d = 0.35$) and RFD ($P = .049$; $d = 0.34$) in the AGP–Pre group versus the CON group, although these did not reach the criterion of ≥85% consistency in the permutation analysis. No significant differences were observed in the magnitude measures of the joint kinematics and kinetics or the movement variability measures of the vGRF, kinematics, and kinetics. The full vGRF results (magnitude and variability measures) are presented in Appendix Tables A1 and A2.

AGP–Pre Versus AGP–Post. Significant changes were observed in the joint kinematics (Figure 2) and kinetics (Figure 3) when comparing the AGP–Pre to AGP–Post states. In addition, nonsignificant changes of small to moderate effect size were observed in the 3 vGRF variables that were significantly different between the AGP and CON groups at baseline testing. Kinematically, significant changes of medium effect size were observed, with decreased pelvic contralateral drop during the entire stance phase of the lateral hop ($d = –0.53$), decreased ankle external rotation throughout the stance phase ($d = 0.39$-0.58), decreased pelvic contralateral rotation during the

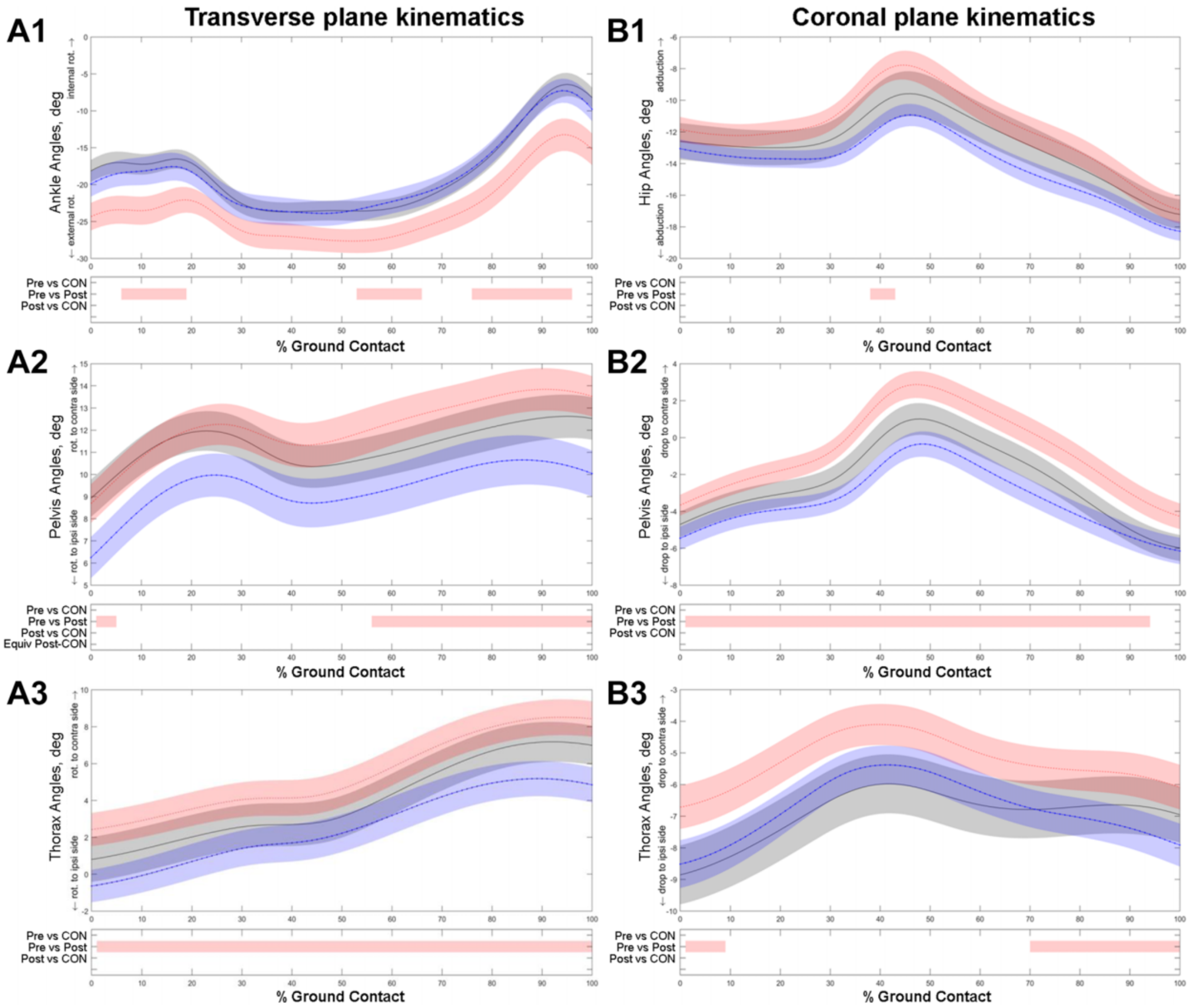

Figure 2. Kinematic changes in athletes in the athletic groin pain (AGP) from before rehabilitation (Pre) to after rehabilitation (Post): (A1) ankle decreased external rotation, (A2) pelvis decreased contralateral rotation, (A3) thorax decreased contralateral rotation, (B1) hip decreased contralateral pelvic drop, (B2) pelvis contralateral drop, and (B3) thorax increased ipsilateral abduction. Waveforms are presented as mean ± SE. Red lines = Pre, blue lines = Post, black lines = controls (CON). The bar below each graph indicates phases of significant difference between groups (Pre vs CON, Pre vs Post, Post vs CON) and of equivalence (Post vs CON).

landing and propulsion phases of the hop (d = –0.45 and –0.27, respectively), and increased thorax ipsilateral abduction during the landing and propulsion phases of the hop (d = –0.55 and –0.46, respectively). There were also significant changes of small effect size for increased hip abduction during the midstance phase of the hop (d = –0.27) and decreased thorax contralateral rotation during the entire stance phase of the hop (d = –0.25) (Appendix Table A3).

Kinetically, significant changes were observed of medium effect size with reduced hip extension moment (d = –0.42) and hip internal rotation moment (d = 0.34-0.41) during the propulsive phase of the hop, and small effect size for reduced knee valgus moment (d = –0.18) during the propulsive phase of the hop (Appendix Table A3). In the vGRF variables, changes of small effect size were observed with decreased CGT (d = 0.39) and concentric impulse (d = 0.29), and increased peak force (d = 0.47), eccentric peak force (d = 0.47), and eccentric RFD (d = 0.40).

Return to Play - AGP-Post versus CON. At return-to-play testing, all 3 vGRF variables that were significantly different between the AGP–Pre and CON groups were no longer significantly different when comparing the AGP–Post and CON groups (total GCT: P = .755, d = 0.08; peak vGRF:

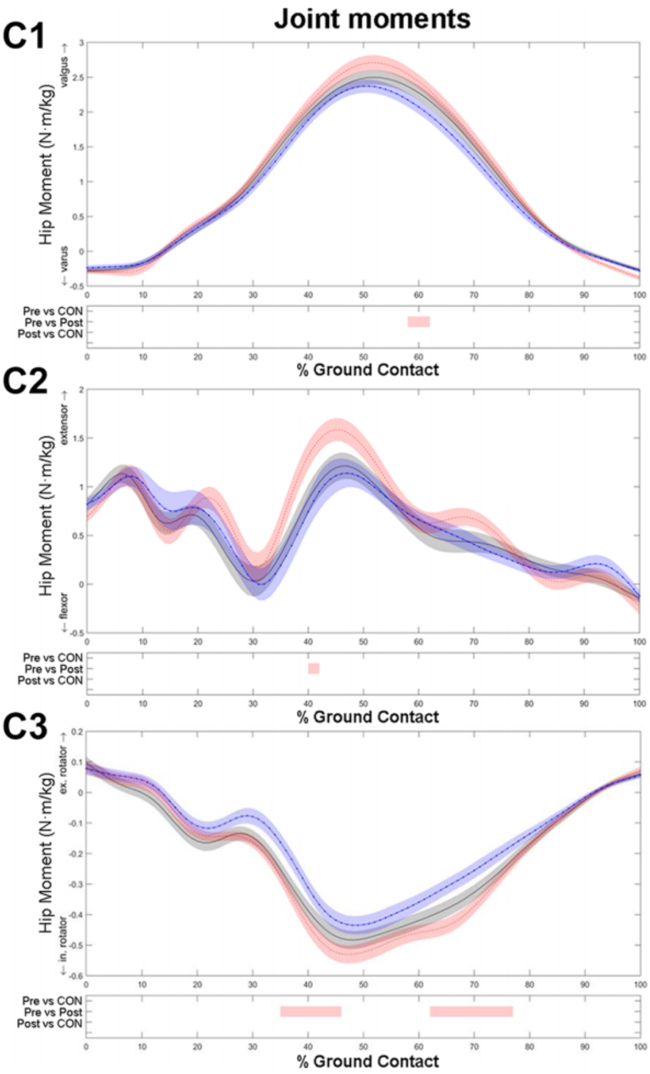

Figure 3. Kinetic changes in athletes with athletic groin pain (AGP) from before rehabilitation (Pre) to after rehabilitation (Post): (C1) knee valgus moment reduced, (C2) hip extension moment reduced, and (C3) Hip internal rotation moment reduced. Waveforms are presented as mean ± SE. Red lines = Pre, blue lines = Post, black lines = controls (CON). The bar below each graph indicates phases of significant difference between groups (Pre vs CON, Pre vs Post, Post vs CON).

$P = .589$, $d = 0.15$; concentric impulse: $P = .478$, $d = 0.20$) (Figure 1). No significant differences were observed in the magnitude measures of the joint kinematics and kinetics or the movement variability measures of the vGRF, kinematics, and kinetics when comparing the AGP–Post and CON groups.

DISCUSSION

This study examined the effect of AGP on the loading characteristics (ie, RFD and impulse) of the vGRF, 3D joint kinematics and kinetics, and movement variability in comparison with uninjured controls and after successful rehabilitation. The AGP group demonstrated significantly increased GCT and concentric impulse, significantly reduced peak vGRF force, and reduced eccentric RFD when compared with the CON group at baseline testing. These differences identified between the athletes with AGP and controls suggest an impaired ability to effectively complete the explosive hurdle hop task and may have resulted from a reduced capacity to load painful tissue structures and/or the subsequent deconditioning postinjury with a reduction in activity (as per the low HAGOS physical activity scores observed in the AGP group at baseline testing). Importantly, after successful rehabilitation, significant changes were observed in trunk and pelvis kinematics and knee and hip kinetics in the athletes with AGP, which resulted in the 3 vGRF measures normalizing in relation to the CON group at return-to-play testing.

These results highlight the importance of examining the loading and movement characteristics in athletes with AGP. In particular, altered control of the trunk, pelvis, and lower limb segments may adversely affect the loading of the myofascial and tendinous structures that attach across to the anterior pelvis.[23,26,35] Therefore, poor movement control of these segments and altered ability to absorb and transmit load across the anterior pelvis may contribute to the propagation of pain in the multiple tissue structures that are commonly found in athletes with AGP.[19,32] As such, it is suggested that rehabilitation aimed at improving intersegmental trunk and pelvis control during explosive sport-specific movements could be used to enhance rehabilitation programs.

It is interesting to note that while differences were found between the AGP and CON groups prerehabilitation for variables derived from the vGRF, no significant differences were found in the joint-level kinematics or kinetics. This may be due to the large degrees of freedom available in coordinating human movement,[5] resulting in different joint-level movement strategies (eg, greater sagittal plane flexion at the hip vs knee vs ankle) being utilized by different athletes. Larger interindividual variability is evident in joint kinematics and joint kinetics compared with vGRF and support moments during walking and running.[14,61] Greater joint-level variability means it is less likely to detect a between-group difference in joint kinematics and kinetics than a difference in vGRF. This study has not attempted to identify subgroups in either how AGP affected movement kinematics and kinetics or how athletes responded to the intervention. Previous research has shown that such subgroups exist in relation to AGP and movement kinematics and kinetics during a 110° task.[23] Therefore, future research may investigate the subgrouping of AGP and how these groups may be affected by an intervention program.

Movement variability, describing the intra-individual variation in motor performance across repetitions of a task, has been theorized to play a functional role in relation to tissue health and overload injuries.[29,34,56] However, we found no differences in movement variability (kinematic, kinetic, and vGRF measures) when comparing the AGP and CON groups pre- or postrehabilitation or in the AGP after successful rehabilitation. In conflicting findings, Edwards et al[18] reported significantly less movement variability at the ankle, knee, and T12-L1 joints and increased movement variability at the L5-S1 joint in the AGP group when compared with the uninjured control group during a running cut task. However, their study appears underpowered statistically, with only 7 AGP participants, which may increase the likelihood of type 1 errors, and they examined the magnitude of movement variability using the coefficient of variation, which has been shown to inflate values when means are close to zero.[7] The conflicting findings may, however, also be explained by the familiarity of the tasks examined. A running cut task, as employed by Edwards et al, would typically be a more practiced movement pattern in field sports athletes as compared with a continuous lateral hurdle hop, and therefore, a more stable pattern has potentially been learned by individuals through practice, as in line with the dynamic system theory of motor learning.[4,11] Therefore, it is possible that the continuous lateral hurdle hop task used in the present study may have resulted in increased movement variability in both the AGP and CON groups, thereby preventing any between-group differences from being observed. However, overall our findings question the importance of movement variability in relation to AGP.

At baseline testing, one of the largest effect size differences between the AGP and CON groups was the longer GCT observed in the AGP group. The longer GCT times were accompanied by reduced peak vGRF and increased concentric impulse in the AGP group; all these variables (peak vGRF, concentric impulse, and GCT) were no longer significantly different when compared with the CON group after rehabilitation. In support of our findings, Gore et al[26] also reported significantly longer GCTs in athletes with AGP during a single-hurdle hop than in uninjured controls.

In our study, there are 2 possible explanations for the longer GCTs and altered vGRF loading characteristics observed in the AGP group. First, the longer GCT and reduced loading characteristics (impulse and eccentric RFD) may reflect a reduction in performance, as athletes were instructed to perform the continuous hops as quickly as possible. The longer GCT in those with AGP may represent a reduced ability to effectively utilize the stretch-shorten cycle (SSC) to enhance the concentric propulsive forces.[22] In line with this, the athletes with AGP demonstrated reduced eccentric RFD and subsequently both reduced peak concentric force and longer concentric GCT when compared with the CON group at baseline testing. Reduced reactive strength has also been previously observed in athletes with AGP when performing a single-leg drop jump when compared with uninjured control athletes.[3] Second, the longer GCT found in the AGP group may represent a compensatory strategy to reduce the peak loading force on the painful structures. This can be explained by the impulse-momentum relationship, in which the AGP group applied a smaller force over a longer time period to control their momentum.[6] Similar compensatory strategies have also previously been reported in athletes with AGP[26] and anterior knee pain.[16]

From a rehabilitation perspective, our intervention program included plyometric exercises that possibly led to enhanced SSC capabilities and increased capacity to minimize the GCT.[41] It has been suggested that the speed of the eccentric action can increase the potentiation effect of the SSC and thus reduce the amount of transition time between the eccentric and concentric phases. In support of this, after rehabilitation, athletes with AGP demonstrated increased eccentric RFD, increased concentric force, and shorter GCT. In addition, decreased GCT has been strongly correlated with increased limb stiffness,[1] which is proposed to play an integral role in the braking phase of fast SSC movements (ie, <250 ms). Therefore, the neural mechanisms underpinning limb stiffness (ie, preactivation and increased neural drive) are likely responsible for the reduced GCT seen in the AGP group. While stiffness was not examined in this study, Gore et al[25] has previously reported significantly less vertical limb and joint stiffness in athletes with AGP compared with healthy participants, which improved postrehabilitation. Measurement of GCTs, which is becoming increasingly accessible within clinical settings with various technologies (eg, force platforms and jump mats), may provide rehabilitators with a simple measure that can reflect improvements in the loading patterns of the GRF; namely, reduced concentric impulse, increased peak vGRF, and increased eccentric RFD.

The lack of significant differences in the joint kinematics and kinetics between the AGP and CON groups at baseline testing is in contrast with previous research.[18,25,26,35,52] In a similar action to the one examined in the current study, Gore et al[26] investigated a single-hurdle hop task and reported significantly less ankle plantarflexion range of motion, reduced ankle plantarflexion moment, reduced hip extension and abduction moments, reduced hip extensor power, and significantly greater knee extension and abduction moments in the AGP group when compared with the uninjured control group. The contrasting findings may be explained by 2 factors. First, different analytic approaches were utilized, with Gore et al employing an “analysis of characterizing phases” approach, which may be less conservative than statistical parametric mapping (as utilized in the current study), which inherently controls for familywise errors. Second, in direct comparison with the Gore et al study, we excluded the initial lateral hop from the stationary start position (as it represented a different movement from all subsequent hops that come directly from a rebound action), whereas Gore et al examined the initial lateral hop from the stationary start position. The continuous hurdle hop task may allow a more measured and controlled action in which forces can be easily modulated, thus avoiding excessive strain on the body resulting in the loss of segmental control. In support of this, altered kinematics have been reported during discrete movement tasks: a running cut[18] and a single-leg drop land[35] in AGP groups when compared with uninjured control groups. Marshall et al[42] examined all 3 of these movement tasks in uninjured athletes (ie, hurdle hop, running cut, and single-leg drop land) and found greater vGRF during the initial eccentric phase (approximately 0%-10% of the movement cycle) in the drop land and running cut task when compared with the hurdle hop. During these tasks (ie, drop land and running cut), which require periods of higher loading in comparison with the hurdle hop, greater compensatory movement patterns may be used by injured populations to reduce the stress placed on the myotendinous structures and joints.[39] Therefore, when examining athletes with AGP, utilizing tasks that provide higher eccentric loading may better expose kinematic and kinetic differences when compared with uninjured athletes.

A number of kinematic and kinetic variables (Figures 2 and 3) demonstrated a significant change of medium effect size from pre- to postrehabilitation in the AGP group. While these changes were not large enough to result in any significant differences in the joint kinematics or kinetics being identified between the AGP and CON groups postrehabilitation, the changes provide additional insight into how athletes with AGP normalized the vGRF variables that were significantly different from the CON group at baseline testing. Of particular importance for rehabilitation, we found that postrehabilitation athletes with AGP demonstrated reduced contralateral pelvis drop, reduced contralateral pelvis rotation, and increased hip abduction. These findings are, in part, supported by Janse van Rensburg et al,[35] who also reported significantly greater contralateral downward pelvic tilt in athletes with groin pain when compared with uninjured controls during a single-leg drop land task.

Our findings possibly reflect improved intersegmental lower limb movement control in the coronal and transverse planes of motion via improved gluteal muscle function given the role of these muscles in assisting with pelvic and hip stability in the coronal and transverse planes of motion.[17,46] In line with this, previous research has identified reduced gluteal muscle activation[44] and strength[3,47] in athletes with AGP. Furthermore, significantly increased hip abductor moment[26] and increased hip abductor stiffness[25] have been identified in athletes with AGP after successful rehabilitation during a single-hurdle hop task. In our study, other kinematic changes after rehabilitation included reduced ankle external rotation, reduced contralateral thorax rotation, and increased ipsilateral thorax side flexion. Previous research has also demonstrated altered ankle and trunk kinematics[26,52] when comparing AGP and uninjured CON groups, which subsequently changed with successful rehabilitation.[10,26,37] Our findings further support the idea that altered mechanics at distal or proximal segments can influence the distribution of loading on the pelvis, as has been previously demonstrated in healthy individuals,[51,53] and thus provide potential targets to enhance rehabilitation in AGP.

In the AGP group after successful rehabilitation, HAGOS scores significantly improved across all subscales, although they remained lower when compared with the scores of the uninjured CON athletes. Lower HAGOS scores when compared with uninjured athletes have previously been demonstrated in athletes with AGP who have made a successful return to play[37] and in athletes who have previously experienced hip and groin pain.[15,57] In the current study, the lower HAGOS scores in the AGP group after successful rehabilitation may be explained by the long duration of pain reported by athletes (mean, 39 weeks), as increased duration of pain duration (>6 weeks) has previously been shown to negatively affect all HAGOS scores.[59]

Even though the HAGOS subscale scores observed in the AGP group after rehabilitation remained significantly lower in comparison with those of the CON group (with the exception of HAGOS Symptoms), 4 of 6 subscales were higher than previously reported lower HAGOS reference limits, which provide cut-points for abnormal subscale scores (ie, 95% reference range for hip and groin injury-free players reported: Pain, 80.1-100; Symptoms, 64.3-100; Activities of Daily Living, 80.3-100; Sport and Recreational Activities [Sport Rec], 71.9-100; Participation in Physical Activity [PA], 75-100; and Quality of Life [QOL], 75-100).[57] In the current study, the HAGOS subscale scores that remained lower than the 95% reference range were the PA and QOL scores. The lower PA and QOL scores after rehabilitation may be explained by the fact that while the athletes with AGP had been cleared to return to play (ie, completing 2 running programs including high-speed and change of direction running), they had not reintegrated into unrestricted training. Given that there are only 2 questions in the PA subscale concerning an athlete's ability to perform at both his or her preinjury performance level and volume/duration of training, it would be difficult for an athlete to achieve "normal" scores in this subscale when first reintegrating into team training after any injury that has resulted in a long absence from unrestricted training.

Limitations

A number of limitations were present in this study. The CON group was only tested at baseline, and therefore, it was not possible to assess the change in variables that may have occurred with continued sporting activity. Furthermore, the AGP group, in undertaking the continuous hurdle hop test at return-to-play testing, may have been more familiar with the test, and this may theoretically produce some improvements in the movement control. However, this test was implemented on average 9 weeks after the initial test, which reduces the likelihood of familiarization being impactful in this situation. If possible, future studies utilizing this study design (ie, injured group prerehabilitation vs injured group postrehabilitation vs uninjured control group) should look to retest the uninjured group.

The continuous lateral hurdle hop test was utilized to allow greater examination of multiplanar movement patterns (as opposed to other commonly examined movement tasks such as vertical jumps, which are generally used to examine variables in a single plane [ie, sagittal]), with these multiplanar actions typical of sports in which AGP is prevalent among athletes.[45,47,48] A continuous hopping task was thought to be superior to the single-hop task to allow a greater insight in movement variability (ie, intraindividual variation in motor performance across repetitions of a task). While beyond the scope of the current study, future research may consider the examination of other movement patterns typical in sports in which AGP is a common presentation (eg, acceleration and running).

In addition, only the magnitude of movement variability was examined, and therefore, it remains unclear if the structure of movement variability was affected. Nonlinear statistics (eg, sample entropy) are required to examine the structure of movement variability, which has been shown to vary independently of magnitude measures.[30] Previous research has reported that the structure of movement variability (ie, complexity) was associated with AGP[24] and should be considered in future research in AGP.

CONCLUSION

Altered loading patterns were identified in the vGRF in athletes with AGP when compared with the uninjured control group, while no differences were found in joint kinematics and kinetics during continuous hurdle hopping. After rehabilitation, athletes with AGP significantly changed their trunk and lower limb kinematics and kinetics that may help to explain the absence of differences in the vGRF variables when the AGP and CON groups were compared at return-to-play testing. Therefore, exercise interventions intended to improve intersegmental trunk and pelvic control may enhance rehabilitation programs targeting athletes with AGP. No differences in movement variability were evident; therefore, our findings do not support the proposed association between altered variability and overuse AGP injury.

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APPENDIX

APPENDIX TABLE A1
Magnitude of the vGRFs During the Continuous Lateral Hurdle Hop[a]

	vGRF			AGP–Pre vs CON			AGP–Pre vs AGP–Post			AGP–Post vs CON		
	AGP–Pre	AGP–Post	CON	*P*	*d*	Cons Sig %	*P*	*d*	Cons Sig %	*P*	*d*	Cons Sig %
GCT, s												
Total	0.276 ± 0.03	0.263 ± 0.03	0.264 ± 0.03	**.025**	0.43	89	.169	0.39	13	.755	0.08	0
Ecc	0.144 ± 0.02	0.138 ± 0.02	0.138 ± 0.02	.064	0.32	53	.225	0.34	6	.770	0.08	0
Conc	0.132 ± 0.02	0.125 ± 0.01	0.126 ± 0.02	**.020**	0.50	97	.190	0.37	9	.702	0.11	0
Force, N/kg												
Peak	32.13 ± 2.88	33.19 ± 3.01	33.61 ± 3.42	**.025**	0.36	88	.098	0.47	31	.589	0.15	0
Ecc peak	32.09 ± 2.90	33.14 ± 3.04	33.58 ± 3.43	**.029**	0.35	82	.096	0.47	32	.580	0.15	0
Conc peak	30.51 ± 2.67	31.28 ± 2.96	31.56 ± 2.71	.054	0.27	52	.163	0.39	11	.663	0.12	0
Impulse, N·s/kg												
Total	5.01 ± 0.45	4.83 ± 0.55	4.94 ± 0.52	.061	0.36	59	.530	0.18	1	.488	0.19	0
Ecc	2.79 ± 0.24	2.74 ± 0.32	2.79 ± 0.29	.277	0.18	1	.735	0.09	0	.554	0.16	0
Conc	2.22 ± 0.25	2.09 ± 0.25	2.14 ± 0.29	**.028**	0.52	86	.317	0.29	4	.478	0.20	0
RFD, N/kg/s												
Ecc	283.84 ± 65.30	309.30 ± 82.85	315.03 ± 87.27	**.049**	0.34	65	.158	0.40	17	.705	0.10	0

[a] Boldface *P* values indicate a statistically significant difference between groups compared ($P < .05$ and Cons Sig $\geq 85\%$). Data are presented as mean ± SD unless otherwise indicated. AGP–Pre, athletic groin pain group before rehabilitation (baseline); AGP–Post, athletic groin pain group after rehabilitation (return to play); CON, uninjured control group; Conc, concentric; Cons Sig %, percentage consistency of $P < .05$; Ecc, eccentric; GCT, ground contact time; RFD, rate of force development; vGRF, vertical ground-reaction force.

APPENDIX TABLE A2
Variability Measures of the vGRFs During the Continuous Lateral Hurdle Hop[a]

	vGRF			AGP–Pre vs CON			AGP–Pre vs AGP–Post			AGP–Post vs CON		
	AGP–Pre	AGP–Post	CON	*P*	*d*	Cons Sig %	*P*	*d*	Cons Sig %	*P*	*d*	Cons Sig %
GCT, s												
Total	0.018 ± 0.01	0.016 ± 0.01	0.015 ± 0.01	.521	0.17	0	.358	0.28	9	.589	0.16	0
Ecc	0.010 ± 0.00	0.009 ± 0.01	0.009 ± 0.00	.392	0.23	0	.323	0.28	3	.692	0.11	0
Conc	0.011 ± 0.01	0.011 ± 0.01	0.010 ± 0.01	.729	0.09	0	.271	0.35	19	.349	0.28	10
Force, N/kg												
Peak	2.410 ± 1.20	2.136 ± 0.99	2.340 ± 1.16	.391	0.25	2	.653	0.12	0	.494	0.20	0
Ecc peak	2.450 ± 1.22	2.180 ± 0.99	2.362 ± 1.17	.406	0.24	1	.635	0.13	0	.529	0.18	0
Conc peak	1.850 ± 0.84	1.791 ± 0.90	1.768 ± 0.93	.707	0.09	0	.601	0.14	0	.685	0.11	0
Impulse, N·s/kg												
Total	0.258 ± 0.11	0.234 ± 0.11	0.247 ± 0.16	.397	0.22	1	.589	0.16	0	.620	0.14	0
Ecc	0.147 ± 0.06	0.131 ± 0.06	0.133 ± 0.08	.363	0.26	0	.464	0.22	6	.651	0.12	0
Conc	0.202 ± 0.07	0.202 ± 0.09	0.188 ± 0.09	.762	0.08	0	.500	0.20	2	.539	0.18	2
RFD, N/kg/s												
Ecc	63.52 ± 26.43	59.37 ± 34.24	55.31 ± 31.79	.463	0.13	0	.364	0.29	13	.578	0.18	3

[a] Data are presented as mean ± SD unless otherwise indicated. AGP–Post, athletic groin pain group after rehabilitation (return to play); AGP–Pre, athletic groin pain group before rehabilitation (baseline); CON, uninjured control group; Ecc, eccentric; Conc, concentric; Cons Sig %, percentage consistency of $P < .05$; GCT, ground contact time; RFD, rate of force development; vGRF, vertical ground-reaction force.

APPENDIX TABLE A3
The Kinematic and Kinetic Changes After Successful Rehabilitation in Athletes With AGP During the Continuous Lateral Hurdle Hop Task[a]

Variable	Movement Plane	Effect Size (Cohen *d*)	Phase of Movement, %	Direction of Change
Kinematics				
Ankle external rotation	Transverse	0.58, 0.39, 0.52	6-19, 53-66, 76-96	↓
Thorax ipsilateral abduction	Frontal	–0.55, –0.46	1-9, 70-100	↑
Pelvic abduction	Frontal	–0.53	1-94	↓
Pelvic contralateral rotation	Transverse	–0.45, –0.27	1-5, 56-100	↓
Hip abduction	Frontal	–0.27	38-43	↑
Thoracic contralateral rotation	Transverse	–0.25	1-101	↓
Kinetics				
Hip internal rotation moment	Transverse	0.41, 0.34	35-46, 62-77	↓
Knee valgus moment	Frontal	–0.18	58-62	↓

[a] ↓, decreased from before to after rehabilitation; ↑, increased from before to after rehabilitation.