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Is stiffness related to athletic groin pain?

S. J. Gore[1,2,3] | **A. Franklyn-Miller**[1,4] | **C. Richter**[1] | **E. C. Falvey**[1,5] | **E. King**[1,6] | **K. Moran**[2,3]

[1]Sports Medicine Research Department, Sports Surgery Clinic, Dublin, UK

[2]School of Health and Human Performance, Dublin City University, Dublin, UK

[3]INSIGHT Centre for Data Analytics, Dublin City University, Dublin, UK

[4]Centre for Health, Exercise and Sports Medicine, University of Melbourne, Melbourne, Australia

[5]Department of Medicine, University College Cork, Cork, UK

[6]Department of Life Sciences, Roehampton University, Roehampton, UK

Correspondence
Shane Gore, Sports Medicine Research Department, Sports Surgery Clinic, Dublin, UK.
Email: shane.gore2@gmail.com

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Abstract

Athletic groin pain (AGP) is a common injury prevalent in field sports. One biomechanical measure that may be of importance for injury risk is stiffness. To date however, stiffness has not been examined in AGP. The primary aim was to determine whether AGP affects vertical and joint stiffness and if so, whether successful rehabilitation is associated with a change in stiffness. Sixty-five male patients with AGP and fifty male controls were recruited to this study. Assessment included a biomechanical examination of stiffness during a lateral hurdle hop test. Subjects with AGP were tested pre- and post-rehabilitation, while controls were tested once. AGP subjects were cleared for return to play in a median time of 9.14 weeks (5.14-29.0). Stiffness was significantly different at pre-rehabilitation in comparison with controls for four of the ten stiffness values examined: ankle plantar flexor, knee extensor, hip abductor, and vertical stiffness ($P < .05$, D = 0.36-0.79). Despite clearance for return to play, of these four variables, only hip abductor stiffness changed significantly from pre- to post-rehabilitation ($P = .05$, D = 0.35) to become non-significantly different to the uninjured group ($P = .18$, D = 0.26). These findings suggest that hip abductor stiffness may represent a target for AGP rehabilitation. Conversely, given the clearance for return to play, the lower sagittal plane and vertical stiffness in the AGP group in comparison with the uninjured controls likely represents either a compensatory mechanism to reduce the risk of further injury or a consequence of neuromuscular detraining.

KEYWORDS
biomechanics, hopping, injury, return to play

1 | INTRODUCTION

Athletic groin pain (AGP) is prevalent in field sports with recurrent accelerations, decelerations, and changes of direction.[1,2] Despite this, the biomechanics contributing to AGP remains poorly understood and under investigated in comparison with other sporting injuries, such as anterior cruciate ligament injury[3] and patella femoral pain syndrome.[4]

Stiffness, which is resistance of a body to deformation under a given load,[5] has attracted attention in injury prevention research[6,7] as a potentially modifiable risk factor.[8] Two types of stiffness are typically measured when examining dynamic athletic tasks, whole-body vertical stiffness, and joint stiffness. Whole-body vertical stiffness reflects the resistance of the center of mass to vertical displacement under a given vertical ground reaction force, and it is often utilized to represent the stiffness of the lower extremity as a whole.[9,10]

Joint stiffness refers to the resistance of a particular joint to rotation under a given moment of force.[5] The majority of studies examine whole-body stiffness, whereas an examination of joint stiffness is advantageous in exploring the contribution of each joint to the sum of whole-body stiffness.

Stiffness can be modulated by the central nervous system to maintain the dynamics of locomotion in response to changes in the environment[5] and task demands.[11] Indeed, it has been demonstrated that stiffness in individual joints of the lower extremity may change when running under varying conditions, while whole-body stiffness can remain constant.[12] As such, it is likely that joint stiffness reflects more closely, localized regions of loading than whole-body stiffness.

Further, it has been suggested that abnormal magnitudes of stiffness may lead to an increased risk of injury by increasing peak force and/or rate of force development,[7] or conversely by increasing the energy absorbed by soft tissues in a lengthened position.[13] In line with this, authors have suggested that high levels of stiffness may be related to bony injuries, while too little stiffness may result in soft tissue injury.[13,14] Previous research has also associated greater stiffness with both stress fracture[7] and contrastingly lesser stiffness with Achilles tendinopathy.[9] With respect to AGP, stiffness may be of particular importance as any alteration in the magnitude of loading or the manner in which loads are absorbed may overload the musculo-tendinous and bony structures surrounding the pubic symphysis region.[15,16] To date however, no research has examined whether stiffness is affected by AGP.

In light of the challenges associated with completing prospective research, identifying factors truly associated with an injury is not often possible. As such, the biomechanical comparison of injured vs uninjured participants is a common research approach.[7,17] While this case-control approach is useful, the findings may not be deterministic of injury (eg, differences may be an outcome of the injury itself), thereby limiting the application of their findings. An alternative but much less common approach is to examine the biomechanical changes that are associated with an effective rehabilitation program (as determined by achieving return to play status). In line with the probabilistic approach to causation,[18,19] the biomechanical factors that change with a successful rehabilitation are possibly causative of the improvements in injury status and therefore more likely associated with the injury. This approach has been utilized with respect to both identifying targets for rehabilitation[20-22] and training interventions for performance.[19,23] Examining the changes that occur with rehabilitation is not without its own limitations of course (eg, it is possible that the observed biomechanical changes following rehabilitation are not related to the underlying injury, but simply associated with the non-rehabilitative effect of the exercise). A more robust approach would therefore be to combine the case-control analysis (injured vs uninjured), the pre-vs post-rehabilitation analysis, and a post-rehabilitation vs uninjured analysis. Logically, the biomechanical factors identified in the case-control analysis (pre-rehabilitation vs uninjured), that change with successful rehabilitation (pre- vs post-rehabilitation) to become more similar to the uninjured group (post-rehabilitation vs uninjured), are more likely to be related to the underlying injury than any of the above approaches in isolation. To date however, this form of analysis has not been conducted in AGP research.

When investigating stiffness, sagittal plane actions, such as running[12] and hopping,[10] are the most commonly used activities examined in this area. However, field sports require dynamic actions not confined to the sagittal plane, and these multi-planar movements are common in sports where AGP is a common presentation.[1,2] A movement stressing frontal and sagittal plane control such as a lateral hurdle hop task[24,25] may thus be a more effective screening test to examine stiffness qualities in AGP patients.

The aim of this study was to determine if AGP affects whole-body vertical and joint stiffness and if so whether a return to play the following rehabilitation is associated with a change in stiffness.

It was hypothesized that (a) prior to rehabilitation the AGP group would be less stiff in comparison with the control group and (b) that stiffness would increase from pre- to post-rehabilitation intervention to become more similar to the uninjured group.

2 | METHODS

2.1 | Participants

Sixty-five male subjects with AGP who had successfully completed the exercise intervention at the Sports Surgery Clinic, Dublin, Ireland, were examined in this study, along with fifty male matched uninjured controls that were recruited from local sporting clubs by direct advertisement. The recruitment period was from January 2014 to March 2015 and comprised of the retrospective inclusion of subjects with AGP who had successfully completed the exercise intervention during this time frame. Inclusion criteria required all AGP participants to undergo clinical consultation, MRI imaging, and physical examination to confirm the diagnosis of AGP as per criteria previously published.[26] Additional inclusion criteria required all participants to be between the ages of 18-35 and involved in multidirectional field sports. In light of recent research by our group,[15] we treat AGP as a single entity (much like lower back pain) and do not restrict inclusion by "entity." Exclusion criteria for AGP participants included the presence of hip joint arthrosis, an underlying medical condition such as inflammatory arthropathy or infection, symptoms less than 4 weeks, lack of intent to return to pre-injury activity levels, and those who did not successfully complete the exercise rehabilitation program. The control group was uninjured but matched to the AGP group based on age, sport, and participation level alongside leg dominance. The Sports Surgery Clinic ethics committee approved the study (REF 25EF011), and all of the participants signed informed consent.

2.2 | Measurements and rehabilitation protocol

AGP subjects completed a three-stage rehabilitation program focusing on intersegmental control and strength, linear running mechanics, and change of direction mechanics, as previously published,[21] and detailed in Appendix S1. Components of strength, power, and plyometric training were incorporated into the rehabilitation program, which as noted in a recent review are all effective means of increasing lower limb stiffness.[8] No aspect of the rehabilitation program was specifically targeted according to pre-rehabilitation stiffness values, but was applied generally to the cohort. The program was unsupervised but a physiotherapist assessed each patient's progress at regular intervals [mean ± SD (range): 4.92 ± 1.7 (2-10) patient assessments every 14.29 ± 3.9 (9-22) days]. Progression from Level 1 to Level 2 of the rehabilitation program was indicated once the patients achieved a negative crossover sign as determined by a lack of pain in the contralateral limb during resisted hip flexion.[27] Patients progressed from Level 2 to Level 3 once the subject achieved symmetrical internal hip rotation at 90°, pain-free squeeze at 45°, and symptom-free completion of the Linear A running program. Patients who demonstrated symptom-free completion of the Linear B running program and multidirectional drills at maximum intensity were deemed sufficiently rehabilitated to be cleared to return to play. No follow-up post-return to play was conducted within this cohort. The Copenhagen Hip And Groin Outcome Score (HAGOS)[28] was examined pre- and post-rehabilitation.

2.3 | Biomechanical examination

Prior to the experimental testing, the subjects completed a standardized dynamic warm-up[25]-a three-minute treadmill jog at 8 km/h, five body weight squats, and five practice trials of the hurdle hop test. The subjects had no other experience of the hurdle hop test. The hurdle hop involved a lateral hop over a 15-cm hurdle followed by an immediate hop back to the initial starting position (Figure 1). The distance between foot contacts was 40 cm (the distance between force plate centers). Reliability for the lateral hurdle hop had previously displayed good to excellent reliability[29] with a median reliability coefficient of 0.89 (range 0.67-0.97) for the biomechanical measures which contribute to the calculation of stiffness (moments and angles).[25] During testing, the subjects wore their own athletic shoes and were instructed to wear the same footwear for both testing sessions where applicable. The AGP participants were examined on their painful side, contralateral non-weight-bearing foot behind with the knee flexed to approximately 90 degrees, and hands unrestricted for balance. Of the 65 AGP patients, 17% had bilateral groin pain. Where the AGP patient had bilateral pain, the leg examined was chosen at random as previously described.[15] Three repetitions of this test were undertaken to obtain mean scores. Participants were instructed to undertake the hop as quickly as possible, and it was the first initial landing phase that was analyzed (Figure 1). Subjects with AGP were tested pre- (AGP pre) and post-rehabilitation (AGP post), while controls were tested once. The post-rehabilitation test was conducted on the day of completion of the rehabilitation protocol.

2.4 | Data capture

Reflective markers (14 mm diameter) were placed at bony landmarks on the lower limbs, pelvis, and trunk as per the Vicon Plug-in Gait model (Vicon Motion Systems, Oxford, UK).[25] Lower extremity kinematics and kinetics were captured. Three-dimensional marker position was tracked using 8 infrared cameras (Vicon-Bonita B10, UK), synchronized with two 40 × 60 cm force platforms (AMTI-BP400600, USA) collecting ground reaction force data. Motion and force data were captured at a sampling frequency of 200 Hz and 1000 Hz, respectively.

2.5 | Data processing

Both marker and force data were filtered using a fourth-order Butterworth filter with a cut-off frequency of 15 Hz.[25]

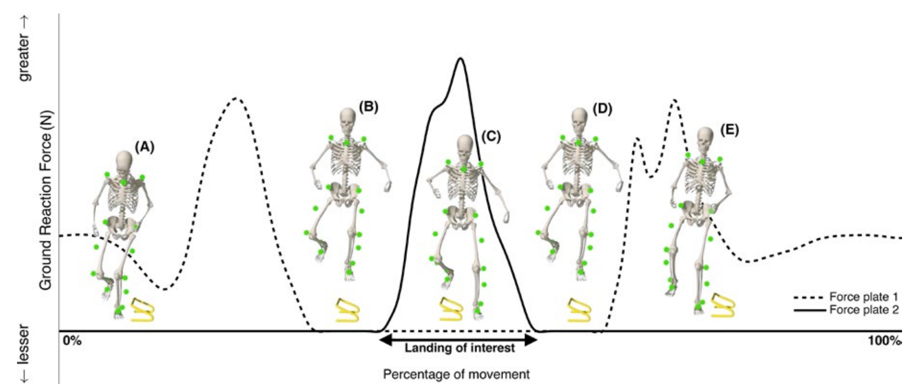

FIGURE 1 Graphical representation of the hurdle hop test. A, Starting position on force plate 1. B, Initial hop over hurdle. C, Initial landing phase that is biomechanically examined on force plate 2. D, Return hop back over the hurdle. E, End position on force plate 1 after hopping back over hurdle

Moment and angle calculations were performed in Nexus software (Vicon Motion Systems, Oxford, UK). The data were subsequently exported to Matlab 2013b (Mathworks, USA) where stiffness was calculated and the statistical analysis conducted. Stiffness was examined during the eccentric phase of the hurdle hop action defined as the period from initial ground contact to peak whole-body negative power. Negative whole-body power was calculated as the external work done per unit time in an attempt to bring the body to a resting state. While many studies have calculated stiffness from initial contact to peak vertical ground reaction force,[10,30] the authors felt the eccentric phase more useful given that the timing of peak vertical ground reaction force varied considerably (mean ± SD: 41.3 ± 12.0% of total ground contact), with 33% of all participants producing their peak force during the whole-body concentric phase. When examining the moment-angle waveforms of the hurdle hop task in this present study, not all joints demonstrated a clear biphasic pattern as presented in previous research.[12,31] Indeed, many moment-angle waveforms demonstrated a polyphasic pattern (Figure 2) with fluctuating moment signs (eg, between positive and negative abductor moments).

In light of these fluctuations, measuring a mean stiffness across varying signs of net moments would produce an erroneous measure of stiffness containing joint moments that are not functionally comparable. For this reason, the current study examined joint stiffness from initial contact to peak whole-body negative power, for phases when the most prevalent eccentric moments were acting (Figure 3). To allow comparison across subjects, the most prevalent eccentric moment was identified at a group level and a moment was deemed to be acting eccentrically when the net joint moment was acting in opposition to the angular displacement of the joint. In the sagittal plane, this involved calculating stiffness for every phase where the extensor/plantar flexor moments acted eccentrically. In the frontal plane, eccentric hip, knee, and ankle abductor/evertor moments were examined. In the transverse, plane stiffness was only calculated when the internal rotator moments acted eccentrically at the hip and ankle, while at the knee, eccentric external rotator moments were examined. For example, in Figure 3 for the calculation of hip extensor stiffness, the previously defined conditions were met at two phases.

For every phase i where these conditions were met, joint stiffness at the hip, knee, and ankle was calculated as the ratio of the change in a joint moment to the change in joint angle for all three planes, from the first to last data point within in phase i. Similarly, vertical stiffness was calculated as the ratio between the change in vertical ground reaction force and the vertical displacement of the center of mass. Both joint and vertical stiffness were subsequently presented normalized to body mass (Equations 1 and 2).

$$\text{Normalised whole body vertical stiffness} = \frac{\Delta \text{Fz.kg}^{-1}}{\Delta \text{COMz}} \quad (1)$$

$$\text{Normalised joint stiffness } (NJS_i) = \frac{\Delta \text{M.kg}_i^{-1}}{\Delta \theta_i} \quad (2)$$

where ΔFz is the change in vertical ground reaction force, ΔCOMz is the displacement of the center of mass, ΔM is the change in a joint moment, and Δθ is the range of motion of the joint.

To adequately represent the mean stiffness of a joint, a weighted mean was required to account for the intermittent nature and varying durations of the included phases (Equation 3):

$$\text{Mean weighted joint stiffness} = [\Sigma_{i=1}^{imax}(NJS_i * \Delta\theta_i)]/\Sigma_{i=1}^{imax}\Delta\theta_i \quad (3)$$

Hop height and hop width were calculated as the vertical and horizontal distance the center of mass traveled from the point of takeoff to the time the center of mass reached its highest point.

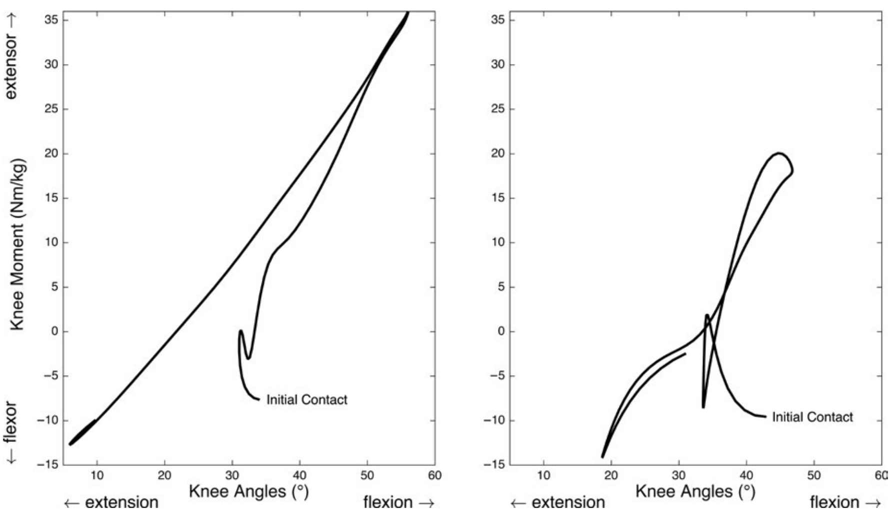

FIGURE 2 Graph depicting a typical biphasic moment-angle pattern as presented in the literature (left) and a polyphasic pattern often identified in this present research (right). Within the polyphasic pattern, the knee angle is fluctuating between periods of extending and flexing coupled with a net knee joint moment fluctuating between extensor and flexor moments

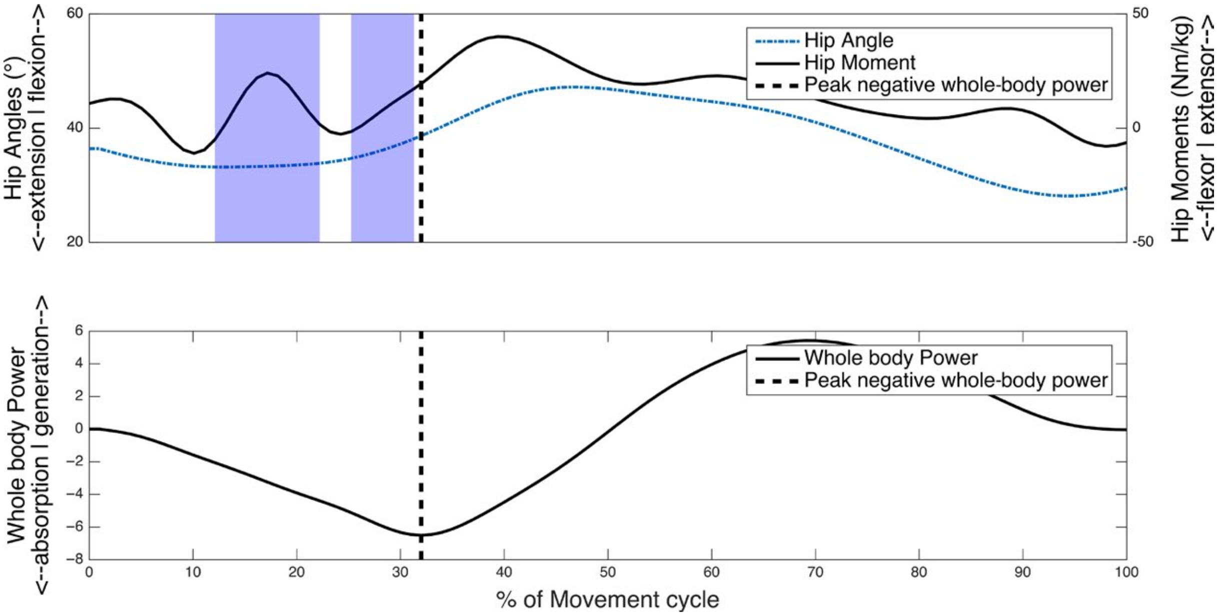

FIGURE 3 Top: Hip flexion/extension angles (°) and Hip flexor/extensor moments (Nm/kg) plotted for a single trial from initial contact to toe off. Shaded region indicates the phases that adhere to the condition of an extensor moment with hip flexion during the period of initial contact to peak whole-body negative power. Bottom: Graph depicting the whole body power (Watt) waveform from the same single trial

2.6 | Statistical analysis

Minimal sample size for statistical purposes was calculated a priori based on pilot results for vertical whole-body stiffness (pre-rehabilitation mean = 0.26, uninjured mean = 0.29, pooled standard deviation = 0.04, power = 0.8, $P < .05$). The analysis demonstrated that at least 45 subjects would be required per group. Independent t tests were utilized to compare AGP results to control results pre-rehabilitation, and paired *t* tests were utilized to compare pre to post changes in the AGP group. No multi comparison adjustment was employed.[32] All results are presented as mean ± SD. Cohen's effect size was reported as small (0.2-0.5), medium (0.5-0.8), and large (>0.8).

3 | RESULTS

3.1 | Subjects

Subject demographics are presented in Table 1. Within the AGP group, a primary clinical diagnosis of a pubic aponeurosis injury was made in 46 (71%) cases; hip flexor injury was diagnosed in 14 (22%) cases; adductor injury was diagnosed in 3 (4%) cases, and inguinal injury was diagnosed in 1 (2%) case. Patients reported a median time of 36 (IQR 24-73) weeks between the onset of symptoms and presentation. Primary sporting participation within both groups was distributed across four sports with the largest proportion of subjects in both groups playing Gaelic football (Table 1).

3.2 | Return to play measures

All AGP subjects completed rehabilitation in a median of 9.14 weeks (IQR 6.6-10.43). The AGP subjects also reported significant improvements in 5 [pain ($P < .01$, d = 0.83), symptoms ($P < .01$, d = 0.75), function in daily living ($P < .01$, d = 0.64), function in sport and recreation ($P < .01$, d = 1.13), quality of life ($P < .01$, d = 1.01)] of the 6 subscales following rehabilitation, with only one subsection [participation in physical activities ($P = .36$, d = 0.38)] not changing significantly (Appendix S2).

3.3 | Stiffness measures

Vertical whole body, ankle plantar flexor, knee extensor, and hip abductor stiffness were significantly less in the AGP pre group in comparison with uninjured control group pre-rehabilitation. When the AGP group was compared pre- and post-rehabilitation, hip abductor stiffness increased significantly and ankle internal rotator stiffness decreased significantly. Post-rehabilitation, vertical whole body, ankle plantar flexor, and knee extensor stiffness remained significantly less in AGP pre group in comparison with uninjured control group, while hip abductor stiffness was no longer significantly different between the two groups (Table 2).

Hop height was not significantly different between the two groups (AGP pre vs uninjured control $P = .32$, d = 0.15, AGP pre vs AGP post = 0.43, d = 0.09) nor was hopping width (AGP pre vs uninjured control: $P = .13$, d = 0.11, AGP

TABLE 1 Subject demographics and breakdown of primary sporting participation

	AGP		Uninjured controls	
Subject demographics				
Age (yrs.)	24.6 ± 4.8 (18-34.92)		23.9 ± 3.4 (20.5-30.6)	
Height (cm)	180.5 ± 5.8 (169.0-193.5)		179.7 ± 9.26 (161.5-202.5)	
Mass (kg)	81.5 ± 8.5 (64.3-110.1)		79.8 ± 13.8 (52.4-107.0)	
	AGP		**Uninjured controls**	
	n	**%**	**n**	**%**
Sporting participation				
Gaelic football	46	70	28	56
Gaelic hurling	7	11	4	8
Soccer	6	10	12	23
Rugby	5	9	6	13

Subject demographics presented as mean ± standard deviation (range).

pre vs AGP post $P = .13$, d = 0.10) and as such were not statistically controlled for in this study.

4 | DISCUSSION

This study investigated if whole-body vertical and joint stiffness are affected in subjects with AGP and if so whether return to play following rehabilitation is associated with a change in stiffness in the AGP group. The main finding from this present study was that using a case-control analysis, the AGP group were significantly less stiff in comparison with controls for four of the ten stiffness variables: ankle plantar flexor, knee extensor, hip abductor, and whole-body vertical stiffness. In contrast, the pre- to post-rehabilitation analysis identified that hip abductor stiffness and ankle internal rotator stiffness changed significantly, while the post-rehabilitation vs uninjured comparison indicated that only hip abductor stiffness was no longer significantly different between the AGP and uninjured group. When examining the biomechanics associated with an injury, previous research has independently reported either case-control (injured vs uninjured)[7,17] or pre- vs post-rehabilitation examinations.[20,21] The strength of the current investigation is that factors identified in the case-control analysis that change with rehabilitation (pre-rehabilitation vs uninjured) and become more similar to the uninjured group (post-rehabilitation vs uninjured) are more likely to represent true targets for AGP rehabilitation.[19] The results from this study suggest that hip abduction stiffness may represent a target for rehabilitation. Within this cohort, the AGP group demonstrated a clinical diagnosis across four entities (pubic aponeurosis, hip flexor, adductor, and inguinal injury). It could be suggested that these clinical entities would exhibit different movement biomechanics and should be examined individually. However, recent research by our group found no relationship between clinical diagnosis and movement biomechanics.[15] Further, Franklyn-Miller et al[15] contend that AGP is caused by an overload of the anterior pubic area (pubic symphysis and surrounding tissues), with various structures becoming painful in direct response to this loading or in an attempt to stabilize the region. For this reason, we treat AGP as a single entity and have examined the cohort within this current study as a whole group.

4.1 | Pre-rehabilitation differences between the control and AGP groups

Prior to rehabilitation, the AGP group were significantly less stiff in several variables in comparison with controls. This is similar to research by Maquirriain[9] who found that athletes with Achilles tendinopathy presented with reduced whole-body vertical stiffness, which the authors hypothesized was due to increased ankle joint compliance resulting from mechanical and material changes to the Achilles tendon.

It is plausible that the lower sagittal plane stiffness seen in our study at the ankle, knee, and whole-body stiffness in the AGP group may represent a compensatory technique. This compensatory technique may reduce loading on the painful pubic symphysis region post-injury. The predominantly vertical orientation of both the resultant ground reaction force and stance limb during the hurdle hop action suggests the magnitude of the ground reaction force is associated with whole-body and sagittal plane joint stiffness. This resultant ground reaction force passes medially to the hip joint center during the hurdle hop and will tend to propagate hip adduction. [While the authors acknowledge the projection of ground reaction forces to predict internal joint moments is erroneous,[33] we feel this interpretation is useful in understanding the influence of sagittal plane joint stiffness on non-sagittal plane stiffness]. To oppose hip adduction, the ipsilateral hip abductors act eccentrically, producing a concomitant increase in ipsilateral hip joint reaction forces.[34] Any increase in the force transmitted from the femur to the pelvis may require adjacent muscular, ligamentous, and cartilaginous structures to assist load transfer and may overload the commonly painful pubic symphysis region which is considered the fulcrum around which many forces are exerted at the pelvis.[16]

It is also possible that the lower stiffness observed in the AGP group was simply due to reduced neuromuscular capacity, particularly at the ankle and knee. Training volume and intensity is often limited in subjects with AGP, to manage the pain,[35] and neuromuscular detraining can occur in as little as 4 weeks.[36] Finally, it is possible that the lower stiffness in the AGP group may reflect a neuromuscular risk factor for AGP with increased joint laxity and strain on localized tissues.

TABLE 2 Whole body and joint stiffness

Stiffness	AGP Pre	AGP Post	Control	AGP Pre vs Control			AGP Pre vs AGP Post			AGP Post vs Control		
Variable	Mean ± SD	Mean ± SD	Mean ± SD	Mean Difference	D	Sig	Mean Difference	D	Sig	Mean Difference	D	Sig
Vertical Stiffness	0.24 ± 0.06	0.25 ± 0.06	0.3 ± 0.07	0.06	0.79	.00	0.01 ± 0.06	0.11	.38	0.05	0.71	.00
Ankle plantar flexor	1.06 ± 0.31	1.07 ± 0.32	1.25 ± 0.38	0.19	0.55	.00	0.01 ± 0.28	0.02	.98	0.18	0.55	.00
Hip abductor	4.06 ± 9.07	7.19 ± 11.29	11.45 ± 23.48	7.39	0.43	.02	3.13 ± 12.60	0.35	.05	4.26	0.26	.18
Knee extensor	3.14 ± 1.65	2.91 ± 1.45	4.05 ± 3.32	0.91	0.36	.05	−0.23 ± 1.80	0.14	.32	1.14	0.45	.02
Knee external rotator	0.25 ± 0.27	0.32 ± 0.38	0.16 ± 0.31	−0.10	0.33	.09	0.07 ± 0.30	0.26	.06	−0.17	0.50	.01
Knee abductor	17.74 ± 51.19	11.15 ± 28.62	9.08 ± 20.84	−8.66	0.21	.27	−6.59 ± 58.92	0.13	.37	−2.06	0.13	.49
Ankle evertor	3.19 ± 5.2	8.8 ± 30.47	2.31 ± 2.69	−0.88	0.20	.29	5.60 ± 28.38	1.08	.12	−6.49	0.27	.16
Ankle internal rotator	1.99 ± 4.49	0.59 ± 1.03	1.29 ± 4.25	−0.70	0.16	.41	−1.40 ± 4.57	0.31	.02	0.70	0.27	.16
Hip extensor	1.46 ± 34.04	4.61 ± 22.19	11.66 ± 118.52	10.20	0.13	.51	3.15 ± 42.34	0.09	.55	7.05	0.01	.96
Hip internal rotator	−2.91 ± 10.54	−1.29 ± 2.62	−2.72 ± 15.62	0.19	0.01	.94	1.61 ± 10.83	0.15	.24	−1.42	0.08	.72

Joint stiffness measured as (Nm.kg^{-1} degrees^{-1}), vertical stiffness measured as (N.m^{-1} kg^{-1}), D = Cohen's D effect size, Sig = significance (*P*). Arranged in order of effect size for AGP pre vs uninjured.

Specifically, the lower hip abductor stiffness in the AGP group pre-rehabilitation was associated with an increased range of hip adduction which may result in an increase in hip adductor activity during single leg stance,[37] and could manifest as increased shear loading at the pubic symphysis.[16]

There were six stiffness measures that were not significantly different in the AGP group in comparison with the uninjured controls pre-rehabilitation (knee external rotator, knee abductor, ankle evertor, ankle internal rotator, hip extensor, and hip internal rotator) and within the scope of this study cannot be deemed to be of relevance to AGP. Given the close proximity of the hip joint to the region of pain in AGP patients, it was unexpected that hip extensor stiffness pre-rehabilitation was not lower in the AGP group. A lower hip stiffness would also have reduced the magnitude of the resultant ground reaction force, which as indicated above is a potential compensatory mechanism for AGP. While the reason for this finding is unclear, it may be related to the hip acting concentrically to extend during the loading phase of the hurdle hop test[25] and maintain an upright trunk.[38] To achieve the task of hopping laterally back over the hurdle (and not hop forward), it would be essential for the athletes in both groups to have an upright trunk at the time takeoff to avoid forward projection of the body's center of mass. While some individuals may maintain an upright trunk throughout the hurdle hop as this would be easier to control, others may prioritize absorbing loads at the hip and are comfortable using a large range of motion. These contrasting demands may also explain the large standard deviations in hip extensor stiffness observed in this current study.

4.2 | Changes in stiffness with rehabilitation

Only hip abductor stiffness increased significantly after rehabilitation to become non-significantly different to the uninjured controls. This suggests that in line with previous research,[17] the hip abductors should be targeted in rehabilitation. It is unclear why only one variable increased in stiffness (three further stiffness measures were lower in the AGP group pre-rehabilitation in comparison with the uninjured controls). While this may indicate that only hip abductor stiffness is of relevance to AGP, it could also be argued that the intervention program was ineffective at targeting stiffness qualities. Indeed, while plyometric exercises are an effective means of enhancing whole-body and sagittal plane stiffness, the volume and intensity of plyometric exercises included within this study were less than previously reported.[8] Furthermore, much of the rehabilitation is focused on posterior chain and lateral hip strength, aimed to enhance hip abductor function, and may have performed so preferentially. These findings may indicate that an intervention with a greater emphasis on increasing joint stiffness may be warranted. However, care should be taken, as if stiffness represents a compensatory mechanism or neuromuscular detraining in AGP, then increasing stiffness in AGP subjects to normative ranges may increase loading on the painful pubic symphysis region. It is the opinion of the authors, however, that a lack of training stimulus may not be the sole explanation for the lack of change in stiffness. Firstly, the training intervention included multiple training modalities (eg, strength, power, plyometrics) that have been shown to enhance stiffness, and secondly all AGP patients in this study returned to pain-free participation in sport, suggesting that whole body, knee, and ankle stiffness are not of relevance to AGP rehabilitation. Future research should prospectively track AGP patients following return to play to determine if stiffness is related to the reoccurrence of this condition and also determine if an intervention with a greater focus on increasing whole body, knee, and ankle stiffness improves the efficacy of AGP rehabilitation.

4.3 | The challenges of measuring stiffness

Generally when examining joint stiffness, the loading phase of a moment-angle graph is assumed to be a clear biphasic pattern.[12,31] However, biphasic patterns are not always present, with fluctuating moments [between agonist and antagonist muscle dominance (Figure 2)] occurring even within the sagittal plane at the knee and hip during sprinting, jumping, hopping, and cutting.[25,39] This results in polyphasic patterns, where we believe it inappropriate to examine a single stiffness measure across the entire waveform (see methods). Within this study, many trials produced no eccentric stiffness (eg, 26% of hip extensor stiffness), which traditionally, if included in stiffness calculations, would lead to erroneous findings. Additionally, even when examining stiffness of a biphasic pattern, net joint moments are often included that are dominated by agonist and antagonist muscle groups (eg, knee extensor and flexors) in a single stiffness measure.[6,31] This is problematic when the moment-angle gradient is nonlinear and suggests the need to screen waveforms and where required utilize alternative stiffness measures such as presented in this study.

4.4 | Limitations

This study examined a lateral hopping action. This provided a more ecologically valid examination of stiffness in field sport athletes; however, it is not known if equivocal results would be obtained if stiffness were examined during a predominantly sagittal motion, as is the norm within the literature.[5,10] To date, within the biomechanics literature, stiffness has been examined as a discrete value (eg, instantaneous stiffness at a specific time point or the average stiffness between two time points). Using a discrete value for stiffness, however, may misrepresent localized periods of high or low stiffness at various time points during the landing phase. To address this limitation, future research should explore continuous signal joint stiffness measures.

Progression through the intervention in this present study was dependent on achieving set criteria. While this is a more ecologically valid approach to rehabilitation than time-based progression, it is important to note that the variation in reassessment time post-rehabilitation may be a confounding factor when examining how a change in stiffness is associated with return to play in this cohort.

Given the focus of this paper on identifying if stiffness is associated with athletic groin pain, only patients who completed the exercise intervention and returned for post-intervention testing were included in this study. As such, potentially important information regarding the mechanics of those who do not successfully rehabilitate is not gained from this study. Finally, given the retrospective nature of this study, it is unclear if the pre-rehabilitation mechanics exhibited by the AGP group are a cause or result of the injury itself. This is particularly pertinent with respect to stiffness given the changes that pain can elicit at a central nervous system level[40] and the dominant role the central nervous system plays with respect to modulating stiffness. Prospective research is, therefore, required to clearly ascertain if stiffness is a risk factor for AGP.

5 | PERSPECTIVES

This was the first study to investigate stiffness in AGP patients. While a causal relationship cannot be investigated within the current study design, it would appear that ankle plantar flexor, knee extensor, hip abductor, and whole-body vertical stiffness are affected by AGP and with the exception of hip abductor stiffness do not improve following clearance to return to play. These findings suggest that hip abductor stiffness may represent a target for rehabilitation in AGP patients. Conversely, it is likely that the lower sagittal plane and whole-body vertical stiffness in the AGP group in comparison with the uninjured controls represent either a compensatory mechanism to reduce the peak magnitude of the hip joint reaction force or is a reflection of detraining. As a result of this study, the authors now believe that hip mechanics in the frontal plane are of particular relevance to AGP and hip abductor stiffness has been further emphasized within the AGP rehabilitation program at the Sports Surgery Clinic. The authors are currently in the process of investigating if rehabilitation with a greater focus on increasing whole body, knee, and ankle stiffness improves the efficacy of AGP rehabilitation. Future research is also warranted to prospectively track AGP patients following return to play to conclusively determine if stiffness is related to the reoccurrence of this condition. To avoid potentially erroneous findings, future researchers examining stiffness should screen moment-angle waveforms and where required utilize alternative stiffness measures, such as presented in this study.

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ORCID

S. J. Gore http://orcid.org/0000-0002-3077-2787
A. Franklyn-Miller http://orcid.org/0000-0002-7826-2209
C. Richter http://orcid.org/0000-0001-6017-1520
E. C. Falvey http://orcid.org/0000-0003-3961-1805
E. King http://orcid.org/0000-0003-0434-1489
K. Moran http://orcid.org/0000-0003-2015-8967

REFERENCES

1. Murphy JC, O'Malley E, Gissane C, Blake C. Incidence of injury in gaelic football. *Am J Sports Med*. 2012;40:2113-2120.
2. Thorborg K, Rathleff MS, Petersen P, Branci S, Hölmich P. Prevalence and severity of hip and groin pain in sub-elite male football: a cross-sectional cohort study of 695 players. *Scand J Med Sci Sports*. 2017;27:107-114.
3. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc* 2009;17:705-729.
4. Neal BS, Barton CJ, Gallie R, O'Halloran P, Morrissey D. Runners with patellofemoral pain have altered biomechanics which targeted interventions can modify: a systematic review and meta-analysis. *Gait Posture*. 2016;45:69-82.
5. Farley CT, Houdijk HHP, Van Strien C, Louie M. Mechanism of leg stiffness adjustment for hopping on surfaces of different stiffnesses. *J Appl Physiol*. 1998;85:1044-1055.
6. Hamill J, Moses M, Seay J. Lower extremity joint stiffness in runners with low back pain. *Res Sports Med*. 2009;17:260-273.
7. Milner CE, Ferber R, Pollard CD, Hamill J, Davis IS. Biomechanical factors associated with tibial stress fracture in female runners. *Med Sci Sports Exerc*. 2006;38:323-328.
8. Brazier J, Bishop C, Simons C, Brazier J, Bishop C, Simons C. Lower extremity stiffness: effects on performance and injury and implications for training. *Strength Cond J*. 2014;36:103-112. Available at: http://journals.lww.com/nsca-scj/Abstract/2014/10000/Lower_Extremity_Stiffness_. Strength … 2014;103–112.
9. Maquirriain J. Leg stiffness changes in athletes with achilles tendinopathy. *Int J Sports Med*. 2012;33:567-571.
10. Brauner T, Sterzing T, Wulf M, Horstmann T. Leg stiffness: comparison between unilateral and bilateral hopping tasks. *Hum Mov Sci*. 2014;33:263-272.

11. Brughelli M, Cronin J. Influence of running velocity on vertical, leg and joint stiffness: modelling and recommendations for future research. *Sport Med*. 2008;38:647-657.
12. Hamill J, Gruber AAH, Derrick TRT. Lower extremity joint stiffness characteristics during running with different footfall patterns. *Eur J Sport Sci*. 2014;14:130-136.
13. Butler RJR, Crowell HHP, Davis IMI. Lower extremity stiffness: implications for performance and injury. *Clin Biomech*. 2003;18:511-517.
14. Williams DS, Davis IM, Scholz JP, Hamill J, Buchanan TS. High-arched runners exhibit increased leg stiffness compared to low-arched runners. *Gait Posture*. 2004;19:263-269.
15. Franklyn-Miller A, Richter C, King E, et al. Athletic groin pain (part 2): a prospective cohort study on the biomechanical evaluation of change of direction identifies three clusters of movement patterns. *Br J Sports Med*. 2017;51:460-468.
16. Meyers WC, Greenleaf R, Saad A. Anatomic basis for evaluation of abdominal and groin pain in athletes. *Oper Tech Sports Med*. 2005;13:55-61.
17. Morrissey D, Graham J, Screen H, et al. Coronal plane hip muscle activation in football code athletes with chronic adductor groin strain injury during standing hip flexion. *Man Ther*. 2012;17:145-149.
18. Spirtes P, Glymour C, Scheines R. *Causation, Prediction, and Search*. Cambridge: MIT Press; 2000:543.
19. Marshall BM, Moran KA. Biomechanical factors associated with jump height: a comparison of cross-sectional and pre-to-posttraining change findings. *J Strength Cond Res*. 2015;29:3292-3299.
20. Thorp LE, Wimmer MA, Foucher KC, Sumner DR, Shakoor N, Block JA. The biomechanical effects of focused muscle training on medial knee loads in OA of the knee: a pilot, proof of concept study. *J Musculoskelet Neuronal Interact*. 2010;10:166-173.
21. King E, Franklyn-Miller AD, Richter C, et al. Athletic Groin Pain (Part 3): an individualised biomechanical approach to rehabilitation. *Under Rev Br J Sport Med* 2018;51:460-468.
22. Snyder KR, Earl JE, O'Connor KM, Ebersole KT. Resistance training is accompanied by increases in hip strength and changes in lower extremity biomechanics during running. *Clin Biomech*. 2009;24:26-34.
23. Sheppard JMJ, Chapman DWD, Gough C, McGuigan MR, Newton RU. Twelve-month training-induced changes in elite international volleyball players. *J Strength Cond Res*. 2009;23:2096-2101.
24. Gore SJ, Marshall BM, Franklyn-Miller AD, Falvey EC, Moran KA. The number of trials required to obtain a representative movement pattern during a hurdle hop exercise. *J Appl Biomech*. 2016;32:295-300.
25. Marshall B, Franklyn-Miller A, Moran K, et al. Biomechanical symmetry in elite rugby union players during dynamic tasks: an investigation using discrete and continuous data analysis techniques. *BMC Sports Sci Med Rehabil*. 2015;7:13.
26. Falvey ÉC, King E, Kinsella S. Athletic groin pain (part 1): a prospective anatomical diagnosis of 382 patients — clinical findings, MRI findings and patient-reported outcome measures at baseline. *Br J Sports Med*. 2015;50:1-9.
27. Brukner P, Khan K. *Brukner & Khan's Clinical Sports Medicine*. NY: McGraw-Hill; 2012:1296.
28. Thorborg K, Hölmich P, Christensen R, Petersen J, Roos EM. The Copenhagen Hip and Groin Outcome Score (HAGOS): development and validation according to the COSMIN checklist. *Br J Sports Med*. 2011;45:478-491.
29. Cicchetti DV. Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology. *Psychol Assess*. 1994;6:284-290.
30. Maloney SJ, Fletcher IM, Richards J. A comparison of methods to determine bilateral asymmetries in vertical leg stiffness. *J Sports Sci*. 2015;34:1-7.
31. Farley CT, Morgenroth DC. Leg stiffness primarily depends on ankle stiffness during human hopping. *J Biomech*. 1999;32:267-273.
32. Perneger TV. What's wrong with Bonferroni adjustments. *BMJ*. 1998;316:1236-1238.
33. Wells RP. The projection of the ground reaction force as a predictor of internal joint moments. *Bull Prosthet Res*. 1981;10–35:15-19.
34. Neumann DA. Kinesiology of the hip: a focus on muscular actions. *J Orthop Sport Phys Ther*. 2010;40:82-94.
35. Hölmich P, Thorborg K. Epidemiology of Groin Injuries in Athletes. In: Diduch D., Brunt L. (eds) *Sports Hernia and Athletic Pubalgia*. 2014. Springer, Boston, MA.
36. Neufer PD, Costill DL, Fielding RA, Flynn MG, Kirwan JP. Effect of reduced training on muscular strength and endurance in competitive swimmers. *Med Sci Sports Exerc*. 1987;19:486-490.
37. Prior S, Mitchell T, Whiteley R, et al. The influence of changes in trunk and pelvic posture during single leg standing on hip and thigh muscle activation in a pain free population. *BMC Sports Sci Med Rehabil*. 2014;6:13.
38. Perry J. *Gait Analysis: Normal and Pathological Function*. Thorofare, New Jersey: SLACK Incorporated; 1992:524.
39. Bezodis IN, Kerwin DG, Salo AIT. Lower-limb mechanics during the support phase of maximum-velocity sprint running. *Med Sci Sports Exerc*. 2008;40:707-715.
40. Hodgesv PW, Tucker K. Moving differently in pain: a new theory to explain the adaptation to pain. *Pain*. 2011;152:S90-S98.

SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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