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Is there a correlation in frontal plane knee kinematics between running and performing a single leg squat in runners with patellofemoral pain syndrome and asymptomatic runners?

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ABSTRACT

Background: Knee kinematics when running, specifically knee valgus, have been linked to patellofemoral pain syndrome. Assessing running biomechanics requires skill, equipment and time. Clinically, the single leg squat is used to make inferences about knee kinematics during running. No evidence supports this practice.

Methods: Sixteen asymptomatic runners and sixteen runners with patellofemoral pain syndrome were recruited. Asymptomatic runners were sub-divided by dominant and non-dominant leg and runners with patellofemoral pain syndrome by painful and non-painful leg. This gave four groups. Participants were videoed performing single leg squats and running on a treadmill. Frontal plane knee kinematics were calculated using the frontal plane projection angle. Correlation in frontal plane projection angle between running and single leg squat were calculated using Pearson's correlation coefficient. Differences in frontal plane projection angle between groups for running and single leg squat were calculated using multiple independent *t*-tests with Bonferroni correction.

Findings: Correlation in frontal plane projection angle between running and the single leg squat was not statistically significant for the painful leg group ($p = 0.19$) but was for the remaining groups ($p < 0.05$). There was no statistically significant difference in frontal plane projection angle between the four groups when running. Single leg squat frontal plane projection angle was significantly larger for the painful leg group (10.3°) than the dominant leg (−0.2° ($p = 0.003$)) and non-dominant leg (−0.4° ($p = 0.004$)) in the asymptomatic runners group.

Interpretation: The single leg squat cannot be used to make inferences about frontal plane knee kinematics in running gait in patellofemoral pain syndrome sufferers.

1. Introduction

Running is an increasingly popular form of exercise (Audickas, 2017) yet up to 70% of runners will be injured each year (Hreljac, 2005). Of all injuries to befall runners, patellofemoral pain syndrome (PFPS) is the most common (Baquie and Brukner, 1997; Macintyre et al., 1991; Taunton et al., 2002). PFPS is defined as pain around and behind the patella in the absence of any specific pathology (Barton et al., 2009). PFPS is therefore a diagnosis of exclusion, with no specific, valid, objective test for diagnosis (Salsich and Perman, 2007). Despite its prevalence PFPS remains poorly understood and treated, with up to 90% of cases recalcitrant to therapy (Stathopulu and Baildam, 2003). With evidence suggesting PFPS is a prequel to patellofemoral joint osteoarthritis (Wyndow et al., 2016a) these figures are evermore concerning.

Despite the prevalence there remains no consensus on the underlying mechanisms of PFPS (Herrington, 2014). Whilst both physical and behavioural factors are implicated (Barton et al., 2015) excessive knee valgus is commonly proposed as causative and it is recommended to assess for this movement pattern during clinical assessment (Manske and Davies, 2016).

Knee valgus is defined by lateral deviation of the distal tibia relative to the centre of the knee in the frontal plane (Perry and Burnfield, 2010). With knee valgus, the patella sits more laterally in the trochlea groove and increases contact pressure at the lateral aspect of the patellofemoral joint (Heino Brechet and Powers, 2002; Chen and Powers,

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Table 1
Inclusion and exclusion criteria.

	Runners with PFPS	Asymptomatic runners
Inclusion criteria – Subjective information	• Vague or localised patella or retropatella pain for > 3 months (Dierks et al., 2011) • Pain > 3/10 numeric rating scale (Farrar et al., 2001) reproduced with running and at least one other of the following (Dierks et al., 2011): o Stair descent o Kneeling o Squatting o Prolonged sitting	• No history of knee trauma within 4 months (Dierks et al., 2008) • No formal diagnosis of knee lesion/pathology (Dierks et al., 2008) • Pain-free when running in last 4 months (Herrington, 2011 • No neurological conditions that could influence gait • (Dierks et al., 2008)
Inclusion criteria – Objective examination	• Non-specific tenderness over the ITB, Vastus Lateralis, lateral retinaculum and medial or lateral patella facet (Brukner and Khan, 2012; Dierks et al., 2011)	• No knee effusion or knee pain (Brukner and Khan, 2012)
Exclusion criteria – Subjective information	• Aged under 18 • Any pre-existing health conditions that prevented running • Unable to give informed, written consent • Not a runner (Rolf, 1995) • History of patella dislocation or fracture (Dierks et al., 2011) • History of lower limb surgery within last 4 months (Mizner et al., 2012)	
Exclusion criteria – Objective examination	Excluded if objective examination or previous imaging suggestive of other pathology, including (Brukner and Khan, 2012): • Ligamentous laxity • Meniscal lesion • Pes anserine lesion • Iliotibial band syndrome • Patellar tendinopathy • Fat pad impingement • Leg length discrepancy	

2014). This increased pressure on the subchondral bone at the lateral facet of the patella has been proposed to cause pain (Gerbino et al., 2006; Cichanowski et al., 2007). The reason people adopt this position is unclear but is likely an interaction of anatomical, postural and muscular factors (Lankhorst et al., 2013).

In support of the theory that knee valgus is an underlying mechanism for PFPS, symptomatic individuals demonstrate greater knee valgus compared to asymptomatic individuals when single leg landing (Herrington, 2014) and performing a single leg squat (SLS) (Herrington, 2014; Levinger et al., 2007; Willson and Davis, 2008). Increased knee valgus during drop jumps has also been demonstrated as a predictor of subsequently developing PFPS (Holden et al., 2017; Myer et al., 2010).

During running however, the evidence linking PFPS and knee valgus is less clear. There is a lack of evidence that knee valgus, as observed in the frontal plane, is of a larger magnitude in PFPS sufferers than asymptomatic individuals when running. When compared to asymptomatic individuals, PFPS sufferers do demonstrate increased hip internal rotation (Souza and Powers, 2009; Wirtz et al., 2012), hip adduction (Dierks et al., 2008; Noehren et al., 2012) and tibial internal rotation (Willson and Davis, 2008) when running. As these factors contribute to the position of knee valgus (Hewett et al., 2006) this may offer some reasoning as to why clinicians draw this conclusion.

The link between knee valgus and PFPS in running is contested by Ferber et al. (2011). They found no difference in 2-dimensional knee valgus measures between asymptomatic individuals and PFPS sufferers when running. Furthermore, Dierks et al. (2011) demonstrated that whilst runners with PFPS do adopt ‘abnormal’ gait patterns only one of the three ‘abnormal’ running gaits they observed was characterised by knee valgus.

Despite the disparity in the evidence base, clinicians assess knee kinematics in the frontal plane, and specifically for knee valgus, as a means of explaining patient symptoms (Barker-Davies et al., 2018; Neal, 2017). However, when assessing runners with PFPS for whom running is the main aggravating factor, running gait analysis is often foregone for reasons that include a lack of skill, time and resources. Assessment of running knee kinematics is instead achieved by interpreting easier to administer assessments such as the SLS (Barker-Davies et al., 2018; Neal, 2017). The practice of doing so is possibly due to the notion that knee valgus is greater in PFPS sufferers when both running and performing a SLS. The movement patterns in each task are therefore presumed to correlate. Alenezi et al. (2014) support this presumption showing that knee valgus during a SLS and running are significantly correlated ($r = 0.59$). Their use of asymptomatic female participants and the availability of only an abstract for review make it both difficult and unwise to generalise these findings to the wider PFPS population. However, rehabilitation that reduces magnitude of knee valgus during a SLS has been shown to have no effect on knee valgus when running (Willy and Davis, 2011). This may suggest heterogeneity to each task with little carry-over. This further brings into question the clinical practice of assuming movement patterns observed during a SLS correlate with those when running - an assumption that in itself is based on inconclusive evidence.

The primary aim of this study is to establish if a correlation exists between frontal plane knee kinematics when running and performing a SLS in asymptomatic runners and runners with PFPS. The secondary aim is to establish if there are differences in frontal plane knee kinematics between symptomatic and asymptomatic individuals when running and performing a SLS.

2. Methods

The methodology gained ethical approval prior to data collection (NRES Committee South Central - Oxford A, 15/SC/0333).

2.1. Participants

Sixteen asymptomatic runners (eleven female, five male) and sixteen runners with PFPS (eleven female, five male) were recruited to the study in accordance with an *a priori* power calculation. Power calculations were powered to 0.8 with an alpha level of 0.05 (Lock et al., 2012). Calculations were based on a standard deviation of 5° of knee valgus during running and a SLS (Herrington, 2014) and a minimal clinically important difference of 5° during the same tasks (Herrington, 2014). In the absence of any consensus on classification within existing literature, participants were considered a runner if they stated that they currently ran for fitness and that running was their predominant

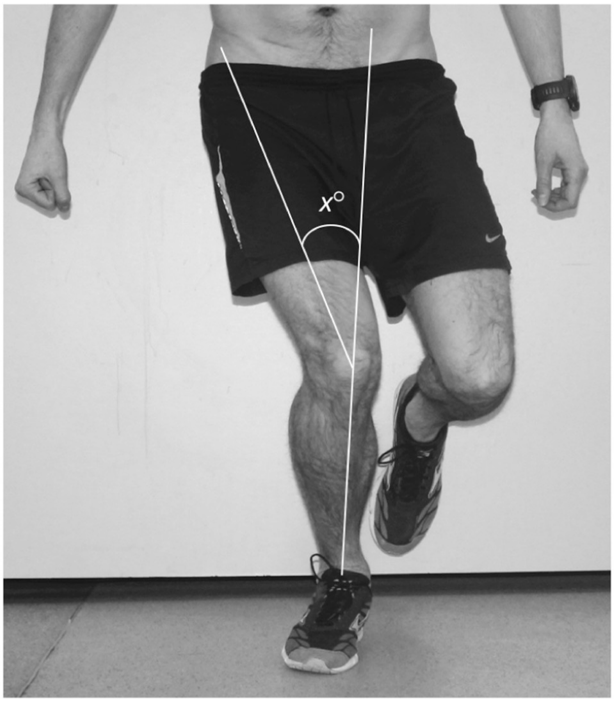

Fig. 1. The frontal plane projection angle (marked as x°).

physical activity (Rolf, 1995). The inclusion/exclusion criteria were based on previous studies as detailed in Table 1. The criterion aimed to exclude individuals with conditions that could affect lower limb mechanics whilst reflecting commonly reported symptoms of PFPS.

Asymptomatic runners were recruited from local running and triathlon clubs *via* email invitation. They became the ‘asymptomatic runners cohort’ and were sub-divided by ‘dominant leg’ and ‘non-dominant leg’. Leg dominance was determined by asking participants which leg they would kick a ball with (van Melick et al., 2017). The runners with PFPS were recruited from the physiotherapy department of a London hospital. Patients were approached by their treating physiotherapist if they met the inclusion/exclusion criteria. The ‘runners with PFPS cohort’ was sub-divided by ‘painful leg’ and ‘non-painful leg’. Consequently, the two recruited cohorts became four distinct groups.

The runners with PFPS were exclusively recruited at their initial physiotherapy assessment to minimise the effect of current treatment as a confounding factor. All participants underwent a physical examination by the principal investigator (DR) to exclude other pathologies. The sex ratio of participants in the runners with PFPS cohort developed organically through the recruitment process to give a representative sample of injured runners seeking treatment in London, United Kingdom. The final sex ratio in the runners with PFPS cohort was matched in the asymptomatic runners' cohort.

2.2. Study protocol

A cross-sectional, quantitative, observational trial was conducted. Prior to participating all subjects read a Participant Information Sheet and were given the opportunity to ask questions. They subsequently signed a consent form. Participant height, weight and age were recorded. Following recruitment all participants followed the same protocol.

Participants were randomised to performing the SLS or running component of the study first by using block randomisation (blocks of four) from an online generator (Dallal, 2007). The randomisation process was performed separately for the runners with PFPS cohort and asymptomatic runner's cohort. During SLS testing the non-painful leg was assessed first in the runners with PFPS cohort; the non-dominant leg was assessed first in the asymptomatic runner's cohort (Ford et al., 2003). All participants had both legs video recorded for analysis. Participants were asked to undertake a five-minute warm-up on an exercise bike and attain a heart rate over 120 bpm prior to testing (Dierks et al., 2008).

2.2.1. Single leg squat

Prior to performing the SLS, subjects viewed an instructional video explaining the test. This detailed the aimed speed and depth of the SLS. Participants practiced the SLS five times on each leg before having five trials videoed. During their practice, participants were given verbal feedback over the aimed depth and speed of the SLS to standardise the procedure. The total time for a participant to complete one SLS (both down and up) was standardised to 3 s. The speed was controlled by a metronome. The aimed SLS depth was 45° knee flexion (Willy and Davis, 2011). Participants were instructed to flex their contralateral knee sufficient that the foot was clear of the floor during the procedure. No further coaching on technique was offered (Mizner et al., 2008).

2.2.2. Running

Participants ran on a treadmill and were asked to slowly increase their speed until it best represented their own training/running pace (Willy and Davis, 2011). This was deemed more representative of participants' normal running style than pre-set speeds (Queen et al., 2006). After five minutes of running at this pace, five consecutive strides were videoed (Willy and Davis, 2011). Running speed was recorded.

2.3. Equipment

Participants were video recorded using a digital camera (Canon EOS 550D) recording at 30 Hz (Mizner et al., 2012). For both the SLS and running tasks, the camera was placed 3 m in front of the participant and at knee height (Mizner et al., 2012). All participants ran on an Xterrra Trail Racer 3.0 treadmill (Xterra, Arkansas, USA). Participants wore running clothing that enabled the body markers described in Section 2.4 to be clearly visible. Where it obscured the view of anatomical markers, clothing was held up by an elastic band. Participants wore their own footwear during running and SLS assessments.

2.4. Data processing

The main outcome measure was the frontal plane projection angle (FPPA). The FPPA is calculated as the angle at which two lines cross. At the knee these lines are drawn from mid ankle mortise to mid tibiofemoral joint and from anterior superior iliac spine (ASIS) to mid tibiofemoral joint (Herrington, 2011) (Fig. 1). The FPPA is a reliable (Munro et al., 2012) and valid 2D measure (Milner et al., 2011) of knee kinematics that generates results comparable with 3D analysis (Mizner et al., 2012).

Videos were manually advanced frame by frame (by DR) and freeze-framed at the frame best representing peak knee flexion for both running and the SLS (Mizner et al., 2012). Peak knee flexion was determined as the frame representing the lowest point of movement of the patella (Munro et al., 2012). The freeze-frame image was imported into open access image processing program ImageJ2 (U.S. National Institutes for Health, Maryland, USA) for analysis. ImageJ2 enables analysis of scientific images (Abràmoff et al., 2004). The FPPA was calculated as the average of the first three readable trials (Herrington et al., 2015; Wyndow et al., 2016b). If the knee was in a position of valgus this was recorded as a positive angle. If the knee was in a position of varus this was recorded as a negative angle.

2.5. Statistical analysis

Independent samples *t*-tests were used to assess for between-cohort

Table 2
Mean baseline characteristics for runners with PFPS and asymptomatic runners.

	Runners with PFPS	Asymptomatic runners
Age (years)	32.4 (4.6; 25–42)	31.7 (3.0; 27–36)
Height (cm)	171.7 (9.7; 155–188)	171.1 (8.6; 157–187)
Weight (kg)	65.6 (9.3; 50–80)	65.5 (8.9; 49–80)
Sex (n)		
Male	5	5
Female	11	11
Treadmill speed (km/h)	6.6 (0.8; 5.0–8.3)	6.9 (1.3; 5.0–9.7)
Leg dominance (n)		
Right	16	16
Left	0	0
Symptomatic leg (n)		
Right	8	n/a
Left	8	n/a

(Standard deviation; range.)

differences in baseline characteristics of age, height, weight, and treadmill speed. A Pearson's correlation coefficient was used to assess the strength of correlation between the SLS FPPA and running FPPA. The strength of correlation was described using guidelines outlined by Hopkins et al. (2009) whereby a correlation coefficient (r) of 0.0–0.1 was described as trivial, 0.1–0.3 as small, 0.3–0.5 as moderate, 0.5–0.7 as large, 0.7–0.9 as very large and 0.9–1.0 as extremely large. Multiple independent samples *t*-tests with Bonferroni correction were performed to assess for any statistically significant difference in FPPA between groups for both running and a SLS (Lock et al., 2012). For all analyses the level of statistical significance was set to $p < 0.05$. Statistical analysis was undertaken using IBM SPSS Statistics version 22.0 (IBM Corp., New York, USA) (IBM Corp, 2013).

3. Results

Baseline demographics of age, height, weight and treadmill speed did not significantly differ ($p > 0.05$) between the runners with PFPS cohort and asymptomatic runners' cohort (Table 2). In the runners with PFPS cohort equal numbers had pain on their dominant (n = 8) and non-dominant leg (n = 8). No collected data was lost and no participants withdrew.

There was a moderate correlation for FPPA when running and performing a SLS in the painful leg group, but this was not statistically significant ($p = 0.19$). The correlations for all other groups were large or very large and were statistically significant ($p < 0.05$) (Table 3).

Multiple independent *t*-tests with Bonferroni correction revealed the SLS FPPA for the painful leg was significantly larger than both the dominant leg group ($p = 0.003$) and non-dominant leg group ($p = 0.004$). No other statistically significant differences in FPPA existed between groups for the SLS ($p > 0.05$). Multiple independent *t*-tests with Bonferroni correction showed no statistically significant difference between any of the four groups for running FPPA ($p > 0.05$) (Table 4).

4. Discussion

The findings of this study suggest that the SLS cannot be used to draw inferences about knee kinematics in the frontal plane during running gait in runners with PFPS. The clinical practice of using the SLS to screen for 'abnormal' running mechanics in runners with PFPS when running (Barker-Davies et al., 2018; Neal, 2017), is therefore not supported by this study. It is not possible to comment on causality or reasoning for this lack of significant correlation as contributing factors were not investigated. Whilst these results suggest heterogeneity to the tasks with little carry-over in movement patterns, the large to very large significant correlation found in every other group (non-painful leg of runners with PFPS and the dominant and non-dominant leg of asymptomatic runners) suggests a unique effect of PFPS. Perhaps the work of Dierks et al. (2011) offers some explanation. They found that runners with PFPS adopt one of three 'abnormal' running gaits, and only one of these gaits was characterised by knee valgus. If this diversity of running patterns held true for the runners in this tested cohort, the inconsistency in knee position could account for the lack of correlation in runners with PFPS.

The statistically significant level and large to very large strength of correlation in all three asymptomatic groups tested (non-painful leg of PFPS runners, dominant and non-dominant leg of asymptomatic runners) suggests that the SLS could be used to draw inferences about knee kinematics in the frontal plane when asymptomatic runners are running. This statistically significant level of correlation in the asymptomatic groups tested agrees with previous research by Alenezi et al. (2014). However, as only abstracts are available for Alenezi et al.'s (2014) research it is not possible to compare or critique the methodology used and drawing any inferences from or comparisons to these findings is unwise.

The three asymptomatic groups investigated demonstrated that SLS FPPA was correlated with running FPPA, whereas the correlation for the FPPA when running and performing a SLS for the painful leg of runners with PFPS was not statistically significant. Hence, it may be of interest to consider whether the assessment of SLS and running FPPA, in asymptomatic runners, could be used to predict which asymptomatic runners were at risk of becoming symptomatic due to 'abnormal' FPPA values. An asymptomatic runner may exhibit an atypical running style or SLS mechanics but are yet to develop symptoms. It may be possible to identify, through future research, a threshold value for 'at risk' FPPA's whereby the SLS and running FPPA would not be correlated, as observed in the symptomatic group in the current study. If this is the case, preventative treatment directed at asymptomatic runners at risk of developing PFPS may reduce their likelihood of developing this condition.

The results of this study demonstrated that, when running, knee kinematics in the frontal plane are no different between runners with PFPS and asymptomatic runners. These findings agree with Ferber et al. (2011) who found no differences in 'peak genu valgum' when running between PFPS sufferers and asymptomatic controls. Peak genu valgum is another validated 2-D measure of knee valgus (McLean et al., 2005; Ferber et al., 2011). This perhaps suggests that PFPS is not solely underpinned by biomechanical factors, and specifically, knee valgus. It is however noted, that whilst not statistically significant, the painful leg group did exhibit greater knee valgus than all other groups whilst running. As both running (Nunes et al., 2018) and increasing magnitudes of knee valgus (Heino Brechet and Powers, 2002; Chen and

Table 3
Pearson's correlation coefficient for frontal plane projection angle when running and performing a single leg squat.

Group	Pearson's correlation coefficient (r) (confidence interval)	Correlation descriptor	Level of significance of correlation (p)
Runners with PFPS - Painful leg	0.34 (−0.13–0.64)	Moderate	0.19
Runners with PFPS - Non-painful leg	0.52 (0.01–0.83)	Large	0.04*
Asymptomatic runners - Dominant leg	0.64 (0.20–0.90)	Large	0.01*
Asymptomatic runners - Non-dominant leg	0.75 (0.40–0.92)	Very large	0.001*

* Statistically significant correlation ($p < 0.05$).

Table 4
Mean frontal plane projection angles for running and single leg squat in asymptomatic runners and runners with PFPS.

	FPPA runners with PFPS		FPPA asymptomatic runners	
	Painful leg group	Non-painful leg group	Dominant leg group	Non-dominant leg group
Mean FPPA for running (degrees (SD; range))	4.7° (4.4°; −4.3°–11.0°)	3.2° (4.0°; −5.3°−11.0°)	1.9° (4.2°; −8.2°−8.8°)	1.2° (5.9°; −14.3°−11.1°)
Mean FPPA for SLS (degrees (SD; range))	10.3°[a,b] (8.2°; 3.7°−27.8°)	6.3° (8.6°; −4.1°−20.7°)	−0.4°[a] (8.6°; −17.2°−13.8°)	−0.2°[b] (7.6°; −18.5°−10.1°)

[a] Statistically significant difference ($p < 0.05$) between SLS FPPA 'Runners with PFPS – Painful leg group' and 'Asymptomatic runners – Dominant leg group'.
[b] Statistically significant difference ($p < 0.05$) between SLS FPPA 'Runners with PFPS – Painful leg group' and 'Asymptomatic runners – Non-dominant leg group'.

Powers, 2014) elevate patellofemoral joint pressure it is plausible that when these small increases coexist they may be sufficient to induce pain. Therefore, these small differences in FPPA may be clinically, if not statistically, important.

The current study demonstrated that during a SLS, runners with PFPS presented with greater knee valgus on their painful leg when compared to asymptomatic runners. These findings agree with past research (Herrington, 2014) and hence increase confidence that the current sample is representative of the general population.

The major strength of this study is the use of a symptomatic PFPS running population. Past literature exploring the relationships between knee valgus when performing a SLS and running (Alenezi et al., 2014) has used asymptomatic populations. Hence the current research provides evidence specific to this symptomatic population.

A potential limitation was the absence of blinding of the principal investigator (DR) to group allocation and hence the potential for bias during data processing. Finally, whilst the sample size met the *a priori* sample size calculation requirements the number of participants in each group was small (n = 16). Whilst sample size was similar to previous research in this area (Alenezi et al., 2014) it had the potential to underpower the study. Specifically, a larger cohort could affect the non-significant correlation found in the painful knee group. In addition, if subgroups of 'abnormal' kinematics during running exist in runners with PFPS (Dierks et al., 2011) a larger cohort may have demonstrated such sub-groups. Due to small sample size in this study, sub-group analysis of the symptomatic participants was not performed.

Future research could investigate the extent to which knowledge of assessment procedures affects the performance of the task, specifically the SLS. Whilst all participants in this study were recruited prior to commencing their current course of physiotherapy, runners with PFPS may have undergone previous episodes of care due to poor therapy outcomes (Stathopulu and Baildam, 2003). Prior knowledge on the perceived 'correct' SLS technique, gained from previous episodes of care, or from running clubs or peers, may alter a person's 'normal' SLS performance. Etnoyer et al. (2013) demonstrated that video and oral instruction can reduce knee valgus during a jump-landing task despite no change in muscular strength. This suggests a degree of conscious control over movement patterns. Any such conscious performance adaptations directed at 'improving' lower limb alignment during the SLS, may influence the correlation between SLS and running FPPA, and hence affect the utility of this clinical assessment procedure.

The effect of running speed on frontal plane knee kinematics is a further area of research to be explored. Orendurff et al. (2018) found that as running speed increased so did peak knee flexion in the stance phase, as observed in the sagittal plane. If running speed were to also effect frontal plane knee kinematics, this may consequentially affect the strength of correlation to frontal plane kinematics during the SLS. Hence, correlation between FPPA during SLS and running may be different in 'faster' compared to with 'slower' runners. It is possible that subgroups may exist dependent of speed and this may affect the ability to draw inferences about running gait from the SLS (*e.g.* strength of correlation may be stronger in 'faster' runners than 'slower' runners).

5. Conclusion

The primary finding of this study is that correlation in frontal plane knee kinematics when running and performing a SLS in runners with PFPS is of moderate strength but not statistically significant. This refutes the clinical practice of using the SLS to draw inferences about frontal plane knee kinematics when runners with PFPS run. Based on the findings the authors recommend the inclusion of a running gait analysis during the assessment of runners with PFPS.

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