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Review

Kinematic gait characteristics associated with patellofemoral pain syndrome: A systematic review

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ABSTRACT

Development of patellofemoral pain syndrome (PFPS) is considered to be multifactorial. The aims of this systematic review were to (i) summarise and critique the body of literature addressing kinematic gait characteristics associated with PFPS; and (ii) provide recommendations for future research addressing kinematic gait characteristics associated with PFPS. A comprehensive search of MEDLINE, EMBASE, CINAHL, and Current Contents revealed 561 citations for review. Each citation was assessed for inclusion and quality using a modified version of the 'Quality Index' and a novel inclusion/exclusion criteria checklist by two independent reviewers. A total of 24 studies were identified. No prospective studies with adequate data to complete effect size calculations were found. Quality of included case–control studies varied, with a number of methodological issues identified. Heterogeneity between studies made meta-analysis inappropriate. Reductions in gait velocity were indicated during walking, ramp negotiation, and stair negotiation in individuals with PFPS. Findings indicated delayed timing of peak rearfoot eversion and increased rearfoot eversion at heel strike transient during walking; and delayed timing of peak rearfoot eversion, increased rearfoot eversion at heel strike, reduced rearfoot eversion range, greater knee external rotation at peak knee extension moment, and greater hip adduction during running in individuals with PFPS. There is a clear need for prospective evaluation of kinematic gait characteristics in a PFPS population to distinguish between cause and effect. Where possible, future PFPS case–control studies should consider evaluating kinematics of the knee, hip and foot/ankle simultaneously with larger participant numbers. Completing between sex comparisons when practical and considering spatiotemporal gait characteristics during methodological design and data analysis is also recommended.

1. Introduction

Patellofemoral pain syndrome (PFPS) is one of the most common musculoskeletal presentations to orthopaedic [1,2], general practice [3], and sports medicine clinics [4–6]. The condition is highly prevalent in adolescents and young adults [7,8], and has been reported to be more common in females than males [5,9,10]. Patellofemoral pain syndrome can be defined as anterior knee pain or retro-patellar pain in the absence of other specific pathology [11]. The anatomical source of the pain remains a highly debated issue but is commonly believed to be the result of elevated lateral patellofemoral joint (PFJ) stress [2,7,8].

The aetiology of elevated lateral PFJ stress and subsequent PFPS development is considered to be multifactorial. Many abnormal kinematic gait characteristics have been hypothesised to contribute to pain development. At the knee joint, altered tibiofemoral rotation and an increase in knee adduction during the stance phase of gait have been proposed to result in lateral patellar tracking and increase lateral PFJ compression [8,12,13]. These kinematic differences could result from structural abnormalities [2], or altered kinematics at the hip or foot and ankle [8,12]. Altered or excessive foot pronation has been hypothesised to increase tibial and femoral internal rotation and lead to greater adduction or medial collapse of the knee [8,12]. Recent research has indicated the presence of decreased hip muscle strength (abductors and external rotators) in individuals with PFPS [1,14,15]. These findings support the theory that increased hip internal rotation and adduction during gait may be a risk factor for PFPS development [8,12,16].

Knowledge of kinematic differences between individuals with and without PFPS is important to health professionals and researchers. This knowledge is needed to develop and optimise valid treatment and prevention strategies for PFPS. A number of research teams have evaluated kinematic variables in individuals with and without PFPS. This has led to a large body of literature

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using various research designs and methods of kinematic analysis to test proposed hypotheses. Therefore, the aims of this systematic review were to (i) summarise and critique the body of literature addressing kinematic gait characteristics associated with PFPS; and (ii) provide methodological recommendations for future research investigating kinematic gait characteristics associated with PFPS.

2. Methods

2.1. Inclusion and exclusion criteria

Prospective and case–control studies published in English evaluating kinematic variables during walking, running, stair negotiation, and ramp negotiation in individuals with PFPS were considered for inclusion. The inclusion criteria required participants to be described as having: *patellofemoral pain syndrome*; *retropatellar, peripatellar, or patellofemoral pain*; *anterior knee pain*; *patella or patellofemoral dysfunction*; *chondropathy*; or *chondromalacia patellae*.

2.2. Search strategy

MEDLINE, EMBASE, CINAHL, and Current Contents electronic databases were searched in May 2009. Searching was limited to the English language only to minimise time and costs related to translation. A search strategy with key words related to diagnosis was taken and modified from the Cochrane systematic review on exercise therapy for PFPS [17]. To narrow the search, a number of key words were applied to each database's search tools to develop the most sensitive and specific search strategy for that database. The following key words were explored in each databases search tools; *biomechanics*, *kinematics*, *motion*, *gait*, *walking*, *locomotion*, *and running*. The strategy and search results are outlined in Table 1.

Following electronic searches, references of included publications were examined, and a cited reference search in the Web of Science (Thomson ISI) for each author of papers found in the electronic search was conducted. Unpublished work was not sought in this review.

2.3. Review process

All titles and abstracts initially identified through the searches were downloaded into Endnote version 9 (Thomson, Reuters, Carlsbad, CA), cross-referenced, and any duplicate references deleted. Each title and abstract was evaluated for potential inclusion by two independent reviewers. If sufficient information was not contained in the title and abstract to determine inclusion, it was retained until the full text could be obtained for evaluation. Any discrepancies between the two reviewers were resolved with a consensus meeting. If consensus could not be reached, a third reviewer was consulted.

2.4. Methodological quality assessment

Two separate scales to assess the methodological quality of each included paper were used. The first scale involved selected components considered relevant to assessing bias of non-randomised studies from the 'Quality Index' developed by Downs and Black [18]. The original scale was reported to have good test–retest ($r = 0.88$) and inter-rater ($r = 0.75$) reliability and high internal consistency (KR-20 = 0.89) [18]. When broken into its subscales, the only aspect reported to possess poor reliability were the items relating to external validity, with both poor internal consistency (KR-20 = 0.54) and reliability ($r = 0.37$).

Due to this apparent weakness in assessing external validity, and the importance of this quality aspect when pooling and summarising data on a clinical population, a second scale to address external validity was developed (see Appendix A). This scale was designed as a checklist to evaluate the ability of each included study to address specific inclusion and exclusion criteria related to the PFPS diagnosis. Each point of the checklist was developed from the consideration of definitions used in published randomised controlled trials (RCTs) [9,10], textbook definitions [19], and discussions between the reviewers.

Both scales were applied by two independent reviewers to each included study. Any discrepancies between the two reviewers were discussed and attempts made to resolve them via a consensus meeting. If consensus could not be reached, a third reviewer was consulted. Inter-rater reliability of each item from both scales was evaluated using kappa (κ) and percentage agreement statistics and the inter-rater reliability of the overall score from each scale was evaluated using intra-class correlation coefficients (ICCs) (model 2, 1), corresponding 95% confidence intervals, and percentage agreement statistics.

2.5. Data extraction and analysis

Means and standard deviations for spatiotemporal gait characteristics and kinematic continuous data from each study were extracted to allow analysis of effect sizes (with 95% confidence intervals and significance using two-tailed t tests without Bonferroni correction). This was done to allow comparison between results from different studies, and between different measurement approaches for similar parameters. Effect sizes and their 95% confidence intervals were then entered into forest plots to allow easy visual comparison. Calculated effect sizes were also categorised as small ($\leq$0.59), medium (0.60–1.19), or large ($\geq$1.20) [20]. If adequate data were not available from original papers to complete effect size calculations (i.e. group means and standard deviations), attempts were made via email and/or post to contact the paper's authors for additional data.

Sample sizes, participant demographics (age, sex, BMI, mass and height), population sources, gait activities investigated, kinematic variables evaluated, and

Table 1
Search strategy and results from each included database.

	Key words	MEDLINE	EMBASE	CINAHL	Current contents
1	Arthralgia/or pain.mp.	281,574	23,660	54,296	140,569
2	Knee joint/or knee/or patella/	37,810	9,454	4,354	0
3	1 and 2	5,119	1,439	1,280	0
4	Anterior knee pain.mp.	503	527	189	582
5	((patell$ or femoropatell$ or femoro-patell$ or retropatell$) adj (pain or syndrome or dysfunction)).mp. [mp = title, original title, abstract, name of substance word, subject heading word]	768	1,138	522	1,188
6	((lateral compression or lateral facet or lateral pressure or odd facet) adj (pain or syndrome or dysfunction)).mp. [mp = title, original title, abstract, name of substance word, subject heading word]	8	17	4	17
7	((chondromalac$ or chondropath$) adj (knee$ or patell$ or femoropatell$ or femoro-patell$ or retropatell$)).mp. [mp = title, original title, abstract, name of substance word, subject heading word]	249	830	52	418
8	or/3–7	1,292	2,322	610	2,069
9	3 or 8	6,092	4,022	1,769	2,069
10	*Biomechanic*[a]	199	29,106	5,757	55,674
11	*Kinematic*[a]	22,026	5,347	2,057	–
12	*Motion*[a]	183,345	6,720	274	6,853
13	*Gait*[a]	12,848	8,823	3,629	12,196
14	*Walk*[a]	17,191	13,861	5,312	10,381
15	*Locomotion*[a]	14,963	21,889	–	14,494
16	*Run*[a]	9273	9,273	2,369	36,513
17	*Stair*[a]	–	–	109	1,456
18	Or/10–18	498,340	112,934	16,972	431,081
19	9 and 19	284	326	142	290
20	Limit 20 to English language and humans	260	272	142	282
21	21 not/letter, review, review article, book, or conference proceedings	217	186	142	264

[a] Key words explored in each database's search tools.

whether spatiotemporal gait characteristics were controlled (i.e. velocity, stride length, and/or cadence) was also extracted from each included study to assist the interpretation of included findings.

3. Results

3.1. Review selection and identification

The initial search yielded 596 citations. Following application of the inclusion/exclusion criteria to each citation's title, abstract and subsequent full text, and a consensus meeting between the two reviewers, the number of citations was reduced to 24 [15,21–43]. Prior to consensus, reviewer one had failed to include one study [36], and reviewer two had included one study which following consensus was deemed not to meet the inclusion criteria. One prospective study [41] was identified but this did not contain adequate data to enable effect size calculations.

3.2. Quality assessment scale validation and methodological quality

Total scores for both of the quality assessment scales, and a breakdown for each individual item on all included papers along with inter-rater reliability results can be found in Tables 2 and 3. The inclusion and exclusion criteria checklist demonstrated at least moderate inter-rater reliability for all individual items (κ = 0.58–1.00) [44], and excellent inter-rater reliability for the overall score (ICC = 0.94) [45]. All individual items from the Downs and Black 'Quality Index' [18] demonstrated at least moderate reliability (κ = 0.40–1.00), with the exception of items 1, 2, 6 and 18. However, these items demonstrated percentage agreements of between 85% and 95%, indicating the presence of a high agreement—low kappa paradox which can result if a low prevalence of some scores exists [46]. The overall score from the Downs and Black 'Quality Index' demonstrated good inter-rater reliability (ICC = 0.86) [18].

3.3. Additional data

Additional data required for effect size calculations was provided by authors for the following papers: Powers et al. [25–27], Crossley et al. [37], Willson and Davis [33], and Souza and Powers [21]. Adequate data were not available to complete effect size calculations for any results from Dillon et al. [43], Anderson and Herrington [42], Hetsroni et al. [41], Heiderscheit et al. [38] and Bolgla et al. [15].

3.4. Methodological data to assist interpretation of results

Sample sizes and participant demographics (age, sex, BMI, mass and height) from each study can be found in Table 4. Population source, gait activities evaluated, variables evaluated, and whether spatiotemporal gait characteristics were controlled for can be found in Table 5.

3.5. Summary of case–control findings

3.5.1. Spatiotemporal gait characteristics

Although not all results were significant, velocity, stride length, and cadence during walking, stair negotiation and ramp negotiation tended to show a trend towards reduction in individuals with PFPS (see Fig. 1A–C). The only significant finding in regards to running characteristics was an increase in support time (ST) [29] in individuals with PFPS (see Fig. 1D).

3.5.2. Walking kinematics

Kinematic findings during walking can be found in Fig. 2. These results indicated greater rearfoot eversion angle at heel strike transient (HST) [24] and delayed timing of peak rearfoot eversion (PREV-time) [30,39] but no difference in peak rearfoot eversion (PREV) [30] or whole foot pronation (PWFpro) [27] in individuals

Table 2
Inclusion and exclusion criteria quality assessment scale results, and inter-rater reliability for each item and the total score.

Paper	Inclusion items (1–3)			Exclusion items (4–7)				Total score
	(1) Clear definition of location	(2) Insidious onset unrelated to trauma	(3) Symptoms consistent with diagnosis	(4) Previous knee surgery	(5) Internal derangement	(6) Ligamentous instability	(7) Other sources of anterior knee pain	
Souza and Powers [21]	1	1	1	1	1	1	1	7
Brechter and Powers [22]	1	1	1	1	1	1	1	7
Brechter and Powers [23]	1	1	1	1	1	1	1	7
Levinger and Gilleard [24]	1	1	1	1	1	1	1	7
Powers et al. [25]	1	1	1	1	1	1	1	7
Powers et al. [26]	1	1	1	1	1	1	1	7
Powers et al. [27]	1	1	1	1	1	1	1	7
Dierks and Davis [28]	1	1	1	0	1	1	1	6
Duffey et al. [29]	1	0	1	1	1	1	1	6
Levinger and Gilleard [30]	1	0	1	1	1	1	1	6
Powers et al. [31]	1	0	1	1	1	1	1	6
Salisch et al. [32]	1	1	1	1	1	1	0	6
Willson and Davis [33]	1	1	1	0	1	1	0	5
Besier et al. [34]	1	0	1	1	0	1	1	5
Grenholm et al. [35]	0	1	0	1	1	1	1	5
Brindle et al. [36]	0	1	1	0	1	1	0	4
Crossley et al. [37]	1	1	1	0	0	0	1	4
Heiderscheit et al. [38]	0	0	1	1	1	1	0	4
Bolgla et al. [15]	0	1	1	1	0	0	0	3
Callaghan and Baltzopoulos [39]	0	1	0	1	0	1	0	3
Nadeau et al. [40]	1	1	0	1	0	0	0	3
Hetsroni et al. [41]	1	1	0	0	0	0	0	2
Anderson and Herrington [42]	0	0	1	0	0	0	0	1
Dillon et al. [43]	0	0	0	0	0	0	0	0
Reliability	0.58	0.88	1.00	0.89	1.00	0.88	0.70	0.94 (0.84–0.98)
%Aggreement	85	95	100	95	100	95	85	70

Table 3
Modified Downs and Black [18] quality index results, and inter-rater reliability for each item and the total score.

Paper	Prospective (P) or retrospective (R) study	(1) Clear aim/hypothesis	(2) Outcome measures clearly described	(3) Patient characteristics clearly described	(5) Confounding variables described	(6) Main findings clearly described	(7) Measures of random variability provided	(10) Actual probability values reported	(11) Participants asked to participate representative of entire population	(12) Participants prepared to participate representative of entire population	(15) Blinding of outcome measurer	(16) Analysis completed was planned	(18) Appropriate statistics	(20) Valid and reliable outcome measures	(21) Appropriate case-control matching	(25) Adjustment made for confounding variables	Total
Hetsroni et al. [41]	P	1	1	0	1	1	1	1	1	1	1	1	1	U	1	U	12
Dierks and Davis [28]	R	1	1	1	1	1	1	1	1	1	0	1	1	U	1	0	12
Bolgla et al. [15]	R	1	1	1	1	1	1	1	0	U	U	1	1	1	1	1	12
Souza and Powers [21]	R	1	1	1	1	1	1	1	1	U	0	1	1	U	U	1	11
Duffey et al. [29]	R	1	1	1	1	1	1	1	1	U	U	1	1	U	1	U	11
Levinger and Gilleard [24]	R	1	1	1	2	1	1	1	U	U	0	1	1	1	U	0	11
Levinger and Gilleard [30]	R	1	1	1	2	1	1	1	U	U	0	1	1	1	U	0	11
Crossley et al. [37]	R	1	1	1	1	1	1	1	0	U	U	1	1	U	1	U	10
Powers et al. [27]	R	1	1	1	1	1	1	1	0	U	U	1	1	1	0	U	10
Salisch et al. [32]	R	1	1	1	1	1	1	1	0	U	U	1	1	U	0	1	10
Willson and Davis [33]	R	1	1	1	2	1	0	1	U	U	0	1	1	U	U	1	10
Besier et al. [34]	R	1	1	1	1	1	1	1	U	U	0	1	1	U	U	1	10
Grenholm et al. [35]	R	1	1	1	1	1	1	1	1	U	0	0	1	U	1	0	10
Powers et al. [25]	R	1	1	1	1	1	1	1	0	U	U	1	1	U	0	U	9
Powers et al. [31]	R	1	1	1	1	1	1	1	0	U	U	1	1	U	U	U	9
Brechter and Powers [23]	R	1	1	1	1	1	1	1	0	U	U	1	1	U	0	U	9
Heiderscheit et al. [38]	R	1	1	1	1	1	1	1	0	U	U	1	1	U	U	U	9
Brechter and Powers [22]	R	1	1	1	1	1	0	1	0	U	U	1	1	U	U	U	8
Brindle et al. [36]	R	1	1	0	0	1	1	1	0	U	U	1	1	U	1	U	8
Callaghan and Baltzopoulos [39]	R	1	1	1	1	1	1	0	U	U	U	1	1	U	U	U	8
Powers et al. [26]	R	1	1	1	1	1	1	0	0	U	U	1	1	U	U	0	8
Nadeau et al. [40]	R	1	1	0	1	1	1	1	U	U	U	1	1	U	U	U	8
Anderson and Herrington [42]	R	1	1	0	1	1	0	0	0	U	1	1	1	U	U	U	7
Dillon et al. [43]	R	1	0	0	1	1	0	0	U	U	U	1	1	U	U	U	5
Reliability		0.00[a]	−0.05[a]	1.00	0.43	0.00[a]	0.83	0.88	0.77	0.64	0.64	1.00	0.00[a]	0.86	0.40	0.69	0.86 (0.68 – 0.94)
%Agreement		95	90	100	85	95	95	95	95	95	95	100	85	95	70	90	30

For items 1–3, 6, 7, 10–12, 15, 16, 18, 20, 21, and 25–0: No, 1: Yes, U: unable to determine.
For item 5–0: No, 1: partially, 2: Yes.
[a] High agreement–low kappa paradox.

Table 4
Sample sizes and population characteristics from each included paper.

Paper	Sample size		Sex (PFPS group)		Age range (mean age)		Mass (kg), height (cm) (BMI)	
	PFPS group	Control group	Male	Female	PFPS group	Control group	PFPS	Control
Anderson and Herrington [42]	20	20	0	20	19–38 (28)	19–39 (29)	62.7, 166 (NR)	62.7, 167 (NR)
Besier et al. [34]	27	16	11	16	Male: NR (30.5) female: NR (28.7)	Male: NR (27.2) female: NR (28.8)	Male: 72.4, 178 (NR) female: 62.7, 168 (NR)	Male: 74.2, 179 (NR) female: 58.3, 166 (NR)
Bolgla et al. [15]	18	18	0	18	NR (24.5)	NR (23.9)	63.1, 170 (NR)	62.1, 170.0 (NR)
Brechter and Powers [23]	10	10	5	5	NR (38.2)	NR (32.0)	70.8, 167.9 (NR)	67.9, 167.2 (NR)
Brechter and Powers [22]	10	10	5	5	NR (38.2)	NR (32.0)	70.8, 167.9 (NR)	67.9, 167.2 (NR)
Brindle et al. [36]	16	12	4	12	18–35 (NR)	18–35 (NR)	NR, NR (NR)	NR, NR (NR)
Callaghan and Baltzopoulos [39]	15	15	0	15	NR (27)	NR (23.5)	61.5, NR (NR)	59.7, NR (NR)
Crossley et al. [37]	48	18	17	31	≤40 (28^)	≤40 (35)	69.5, 170.0 (23.9)	66.3, 172.0 (22.2)
Dierks and Davis [28]	20	20	5	15	18–45 (24.1)	18–45 (22.7)	65.8, 171 (NR)	63.0, 170 (NR)
Dillon et al. [43]	8	11	0	8	NR (NR)	NR (NR)	NR, NR (NR)	NR, NR (NR)
Duffey et al. [29]	99	70	69	30	NR (36.0)	NR (36.0)	69.5, 172.1 (23.3)	70.2, 174.5 (22.9)
Grenholm et al. [35]	17	17	0	17	NR (27.7)	NR (26.0)	63, 167 (NR)	61, 167 (NR)
Heiderscheit et al. [38]	8	8	0	8	19–36 (24)	21–38 (27)	70.1*, 171.0 (NR)	57.9, 170.0 (NR)
Hetsroni et al. [41]	61	344	U	U	NR (NR)	NR (NR)	NR, NR (NR)	NR, NR (NR)
Levinger and Gilleard [24]	11	14	0	11	NR (36.3*)	NR (25.1)	64.9, 166.1 (NR)	61.3, 166.3 (NR)
Levinger and Gilleard [30]	13	14	0	13	NR (38.4*)	NR (25.1)	70.6, 166.3 (NR)	61.3, 166.3 (NR)
Nadeau et al. [40]	5	5	2	3	NR (28.4)	NR (25.5)	67.6, 172 (NR)	67.0, 170 (NR)
Powers et al. [27]	24	18	0	24	15–47 (25.4)	15–47 (27.6)	63.6, 164.9 (NR)	59.6, 165.8 (NR)
Powers et al. [25]	26	19	0	26	14–46 (25.6)	23–38 (27.5)	63.9, 165.1 (NR)	59.2, 165.3 (NR)
Powers et al. [26]	19	19	0	19	14–46 (24.4)	23–38 (27.5)	62.4, 165.1 (NR)	59.2, 165.3 (NR)
Powers et al. [31]	15	10	0	15	14–41 (26.5)	27–37 (31.5)	65.3, 164.3 (NR)	63.7, 170.9 (NR)
Salisch et al. [32]	10	10	5	5	22–55 (36.5)	21–42 (31.9)	70.9, 173.1 (NR)	67.7, 170.7 (NR)
Souza and Powers [21]	21	20	0	21	18–45 (27)	18–45 (26)	64.7, 170 (NR)	62.9, 170 (NR)
Willson and Davis [33]	20	20	0	20	18–35 (23.3)	18–35 (23.7)	61.7, 166.0 (NR)	61.1, 166.0 (NR)

NR = not reported.
* Indicates significant difference ($p < .05$) between groups.

Table 5
Population types, activities, variables, and control or consideration of gait characteristics.

Paper	Population source (PFPS group)	Locomotion activities	Variables measured	Gait characteristics
Anderson and Herrington [42]	Orthopaedic clinic presentation	Stair descent	Sagittal plane knee (2D)	U[a]
Besier et al. [34]	Undefined	Walking and running	Sagittal plane hip, knee and ankle (3D)	U
Bolgla et al. [15]	General population	Stair ascent and descent	Hip in all planes (3D)	C (96 steps/min)
Brechter and Powers [23]	Orthopaedic clinic presentation	Walking	Sagittal plane knee (3D)	U
Brechter and Powers [22]	Orthopaedic clinic presentation	Stair ascent and descent	Sagittal plane knee (3D)	U[b]
Brindle et al. [36]	General population	Stair ascent and descent	Sagittal plane knee (3D)	U[a]
Callaghan and Baltzopoulos [39]	Undefined	Natural walking	Rearfoot eversion (2D)	U[a]
Crossley et al. [37]	General population	Stair ascent and descent	Sagittal plane knee (2D)	C (96 steps/min)
Dierks and Davis [28]	Recreational runners	Running (treadmill)	Coronal plane hip and knee, and transverse plane hip (3D)	U
Dillon et al. [43]	College-age females	Walking on flat and down 15° slope (treadmill)	Sagittal plane knee and ankle (2D) Transverse plane tibia, femur, and pelvis (2D)	C (1.11 m/s)
Duffey et al. [29]	Recreational and competitive runners (≥10 miles/week) of at least 1 year experience	Running	Rearfoot eversion kinematics (2D-treadmill)	U[b]
Grenholm et al. [35]	General population	Stair descent	Sagittal plane knee and ankle, and coronal plane hip (3D)	U
Heiderscheit et al. [38]	General population	Running	Sagittal plane knee and ankle, and coronal plane femur, tibia and ankle kinematics (3D)	C (2.68 m/s)
Hetsroni et al. [41]	Military recruits	Walking (treadmill)	Rearfoot eversion kinematics (2D-treadmill)	C (1.38 m/s)
Levinger and Gilleard [24]	Undefined	Natural walking	Rearfoot frontal plane (3D)	U
Levinger and Gilleard [30]	Undefined	Natural walking	Rearfoot and tibia all planes (3D)	U
Nadeau et al. [40]	Orthopaedic clinic presentation	Natural walking	Sagittal plane ankle, knee and hip (2D)	U
Powers et al. [27]	Undefined	Natural walking	Whole foot pronation and transverse plane tibia and femur (3D)	U[b]
Powers et al. [25]	General population (orthopaedic clinic presentation)	Natural and fast walking Ramp ascent and descent Stair ascent and descent	Sagittal plane knee (3D)	U[a]
Powers et al. [26]	Orthopaedic clinic presentation	Natural and fast walking Ramp ascent and descent Stair ascent and descent	Sagittal plane ankle, knee and hip (3D)	U[b]
Powers et al. [31]	General population	Natural and fast walking	Sagittal plane knee (3D)	U[b]
Salisch et al. [32]	Orthopaedic clinic presentation	Stair ascent and descent	Sagittal plane ankle, knee and hip (3D)	U[b]
Souza and Powers [21]	General population (orthopaedic clinic presentation)	Running	Coronal and transverse plane hip (3D)	C (3.0 m/s)
Willson and Davis [33]	Active females (regular sports participation)	Running	Hip and knee in all three planes (3D)	C (3.7 m/s)

U: uncontrolled and unaccounted for, C: Controlled, 2D: two-dimensional motion analysis, 3D: three-dimensional motion analysis.
[a] Not reported.
[b] Significant differences found.

with PFPS (see Fig. 2A). Limited evidence indicated increased peak ankle dorsiflexion (PAnkDF) [26] but no difference in peak or timing of peak tibial rotation angles [27,30] (see Fig. 2B). Findings of decreased knee flexion at heel strike (KF-HS) [31] and during early stance (KF10 and KF20) [40], and trends towards earlier and reduced peak hip internal rotation (PHIR-time and PHIR) [27] were also indicated during walking in individuals with PFPS (see Fig. 2C). During fast walking, findings from one study indicated increased peak ankle dorsiflexion (PAnkDF) [26] in individuals with PFPS (see Fig. 2D). Additionally, significant reductions [31] or trends towards reductions [23,25] in peak knee flexion (PKF) were indicated in individuals with PFPS (see Fig. 2D).

3.5.3. Stair and ramp negotiation kinematics

Included findings evaluating kinematics during stair/ramp ascent and descent can be found in Fig. 3A and B respectively. During stair negotiation, limited findings indicated no difference in peak hip flexion (PHF) angle [32] or hip adduction at contra-lateral foot strike [35], whilst findings related to knee flexion (PKF and KF-HS) and peak ankle dorsiflexion (PAnkDf) angles [32] were inconsistent. One study found a reduction in knee flexion velocity during stair descent [35] (see Fig. 3B). Only one study evaluating kinematics during ramp ascent and descent was identified [26]. Findings indicated significantly increased peak ankle dorsiflexion (PAnkDF) but no difference in peak knee flexion (PKF) during both ramp ascent and descent in individuals with PFPS (see Fig. 3A and B).

3.5.4. Running kinematics

During running, one study with large participant numbers ($n \geq 70$ in each group) [29] indicated greater rearfoot eversion at heel strike (REV-HS), increased and delayed timing of peak rearfoot eversion (PREV and PREV-time), and reduced range of rearfoot eversion during the first 10% (REVexc10) and the total (REVexc) of stance phase (see Fig. 3C). Another study evaluating running kinematics indicated significantly increased knee external rotation (KER) at peak knee extension moment in individuals with PFPS [33] (see Fig. 3C). Three studies [21,28,33] evaluating kinematics at the hip during running were identified (see Fig. 3D). However, findings related to hip adduction and internal rotation were inconsistent (see Fig. 3D).

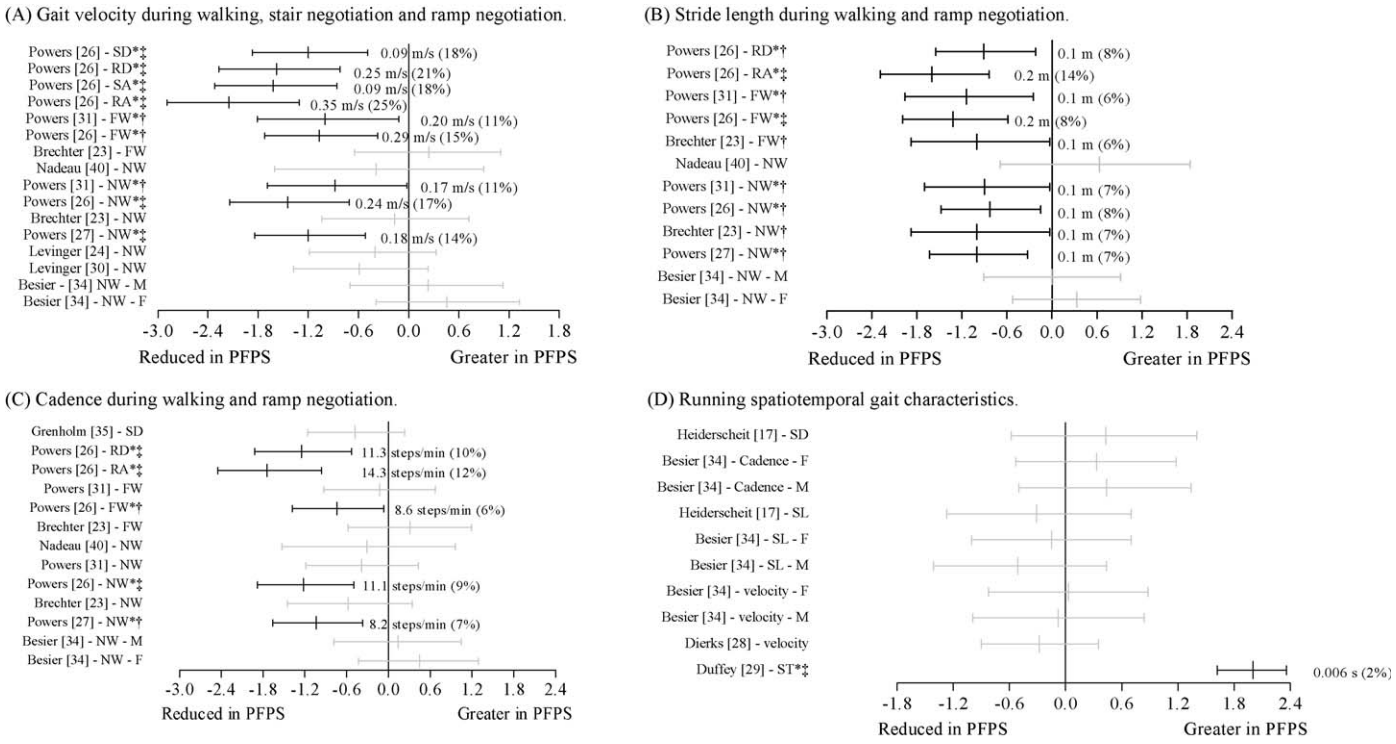

Fig. 1. Spatiotemporal gait characteristics (black plots = significant findings with group difference adjacent the right error bar, grey plots = non-significant findings). (A) Gait velocity during walking, stair negotiation and ramp negotiation. (B) Stride length during walking and ramp negotiation. (C) Cadence during walking and ramp negotiation. (D) Running spatiotemporal gait characteristics. (*) Variables were reported to have statistically significant differences between groups in original study. (†) Medium effect sizes found. (‡) Large effect sizes found. *Variable abbreviations*: M: male, NW: natural walking, F: female FW: fast walking, RA: ramp ascent, SA: stair ascent, RD: ramp descent, SD: stair descent, SL: stride length, SD: stride duration, ST: support time, m: metres, m/s: metres per second, min: minute.

4. Discussion

The review identified 24 published studies evaluating kinematic gait characteristics associated with PFPS. Various methodological issues were identified in the review, which have implications for interpretation of included findings. These included identification of potential methodological bias, lack of control of or accounting for spatiotemporal gait characteristics which may alter kinematics, different study population definitions and demographics, including participants greater than 40 years of age who may possess PFJ osteoarthritis, varied data collection procedures, and statistical reporting deficiencies. Only one of the 24 included studies contained a prospective research design [41] and this did not contain adequate data to complete effect size calculations. Therefore, the ability to distinguish between cause and effect from this review is limited.

4.1. Considerations when interpreting results

Included studies showed large variations in quality, measured using items from the Downs and Black 'Quality Index' [18], with scores varying between 5 and 12 out of 15. Items 5, 11, 12, 15, 20, 21, and 25 will be discussed further due to generally poor results across included studies (see Table 2). Results from the inclusion/exclusion criteria checklist (see Table 3) and results from Tables 4 and 5 will also be discussed further.

4.1.1. External validity

A number of common methodological weaknesses which limit the external validity of many findings in this review were found. The majority of included studies either recruited participants via convenience sampling (e.g. university population or single source) or did not define their source population (see Table 5). This limits the ability of any findings to be applied to a broader population. The ages of participants from the included studies varied substantially. Common consensus amongst recent RCTs investigating PFPS populations [9,10] would indicate that PFPS patients treated clinically fall into an age range of 18–40 years of age. Younger populations may be considered skeletally immature, whilst older populations may be far more likely to possess PFJ osteoarthritis. Of the 24 included studies, 12 did not define the age range used and seven reported using participants aged greater than 40 years of age.

The majority of included studies focussed on females, with 14 out of 24 (58%) of the included studies reporting to investigate females only. None of the included studies provided adequate comparison between female and male participants for kinematic variables. Since a recently conducted large randomised controlled trial ($n = 179$) using a general population indicated comparative ratios of males to females (44% males) [10], excluding males from evaluation means a large proportion of the PFPS population is not represented. On the inclusion/exclusion criteria checklist, scores varied between 0 and 7 out of 7 (see Table 3). Only seven out of the 24 (29%) included studies reported covering all seven inclusion/exclusion criteria, thus limiting the ability to confidently apply most findings in this review to a PFPS population. Variable results from the inclusion/exclusion quality assessment scale indicating the use of different inclusion/exclusion criteria also limit the ability to pool results from multiple studies.

4.1.2. Confounding factors

Of the 24 included studies only four reported the test–retest reliability of their measurement techniques (item 20 on Downs and Black Quality Index [18]). Items 5 and 25 from the Downs and Black 'Quality Index' [18] relate to identifying and adjusting for confounding variables respectively. Only six studies were found to

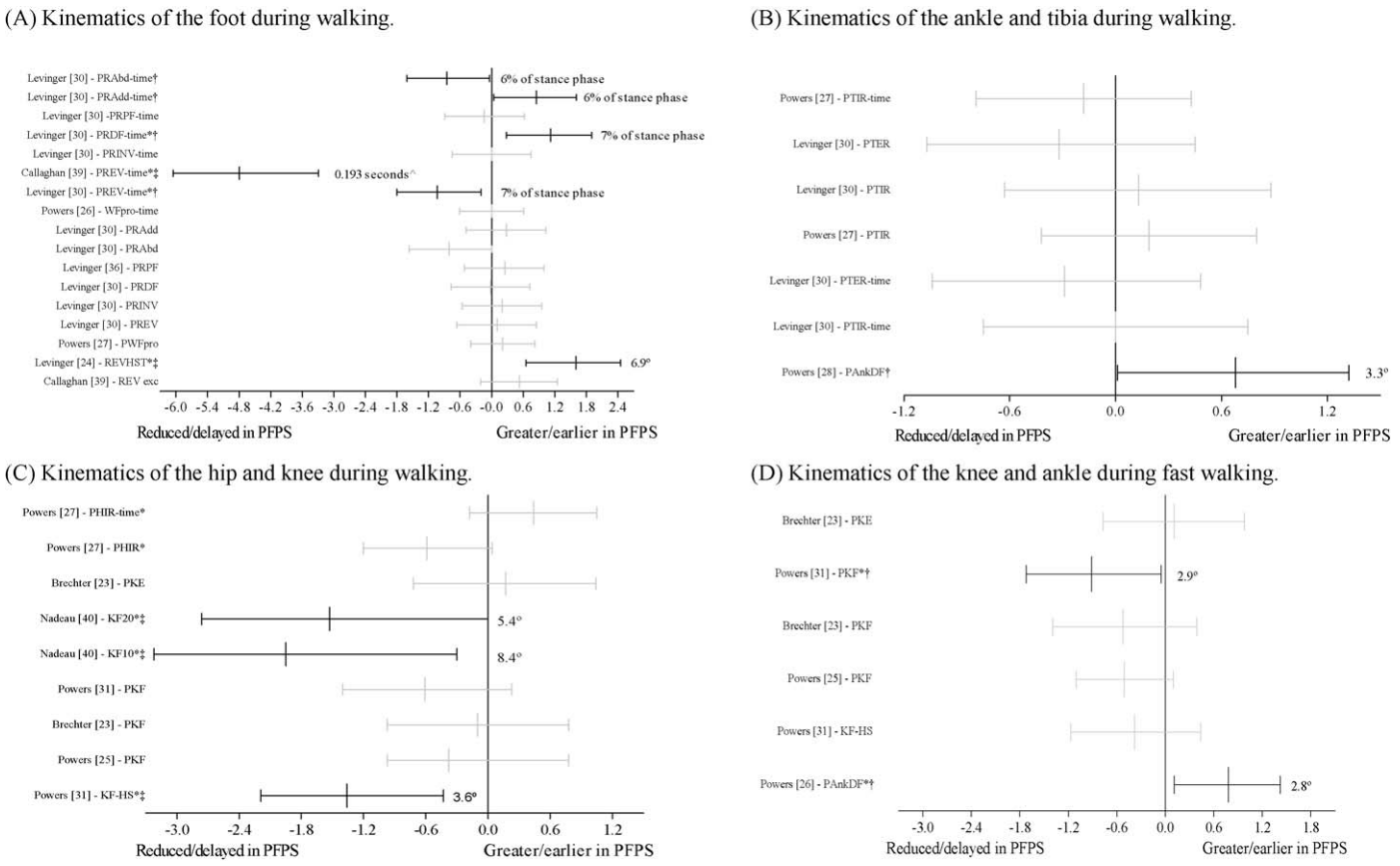

Fig. 2. Kinematics during walking (black plots = significant findings with group difference adjacent the right error bar, grey plots = non-significant findings). (A) Kinematics of the foot during walking. (B) Kinematics of the ankle and tibia during walking. (C) Kinematics of the hip and knee during walking. (D) Kinematics of the knee and ankle during fast walking. (*) Variables were reported to have statistically significant differences between groups in original study. (†) Medium effect sizes found. (‡) Large effect sizes found. (^) Inadequate information to calculate percentage difference. *Variable abbreviations*: time: timing of, PRAbd: peak rearfoot abduction, PRAdd: peak rearfoot adduction, PRPF: peak rearfoot plantar flexion, PRDF: peak rearfoot dorsiflexion, PRINV: peak rearfoot inversion, PREV: peak rearfoot eversion, WFpro: whole foot pronation, REVHST: rearfoot eversion as heel strike transient, PTIR: peak tibial internal rotation, PTER: peak tibial external rotation, PAnkDF: peak ankle dorsiflexion, PHIR: peak hip internal rotation, PKE: peak knee extension, KF20: knee flexion at 20% of gait cycle, KF10: knee flexion at 10% of gait cycle, PKF: peak knee flexion, KF-HS: knee flexion at heel strike.

adequately address either of these items, and only one study [33] adequately addressed both items. Confounding variables considered for studies from this review included matching participant sources and demographics (e.g. age, height, mass and activity levels), and controlling or accounting for differences in spatiotemporal gait characteristics (velocity, stride length and cadence).

Only seven of the 24 included studies controlled spatiotemporal gait characteristics. Of the 17 that did not, six reported significant differences between groups and six did not report sufficient data to evaluate differences between groups (see Table 5). None of the 17 studies not controlling spatiotemporal gait characteristics reported to have accounted for possible differences during statistical analysis.

4.1.3. Spatiotemporal gait characteristic differences

There is some evidence to suggest that spatiotemporal gait characteristics (velocity, stride length and cadence) may be altered in individuals with PFPS. Three [26,27,31] of the eight studies evaluating natural gait velocity found significant reductions in gait velocity, whilst four [23,24,30,40] of the remaining five all showed trends towards reduced gait velocity in individuals with PFPS. Slower velocity was also indicated during fast walking [26,31], ramp ascent and descent [26], and stair ascent and descent [26]. Evidence also indicates that stride length may be decreased in individuals with PFPS during natural [23,26,27,31] and fast walking [23,26,31], and ramp ascent and descent [26]. Similarly, evidence exists for a reduction in cadence in individuals with PFPS during natural [26,30] and fast walking [40], and ramp ascent and descent [26]. Three studies [22,32,35] reported cadence during stair negotiation. However, only one [35] reported adequate data to allow effect size calculations, indicating a trend towards reduced cadence in individuals with PFPS.

Spatiotemporal gait characteristics reported during running included gait velocity, stride length, cadence, stride duration, and support time. One study showed an increase in support time during running in a PFPS population [29], which may indicate a reduction in velocity similar to that observed during walking. However, two other studies [21,28] did not find any significant association between reduced running velocity and PFPS.

The possible presence of reduced gait velocity, stride length, and cadence (see Fig. 1) in individuals with PFPS highlights the importance of controlling or accounting for differences in spatiotemporal gait characteristics, since reduced walking velocity has been reported to decrease joint motion [47–49]. It could also be argued that, controlling gait velocity or cadence as was done in six of the included studies may alter normal gait patterns and subsequently affect kinematics. Therefore, all case–control kinematic comparisons found in this review should be considered with caution, particularly from studies which reported significant differences or did not report spatiotemporal gait characteristics for their populations (see Table 5).

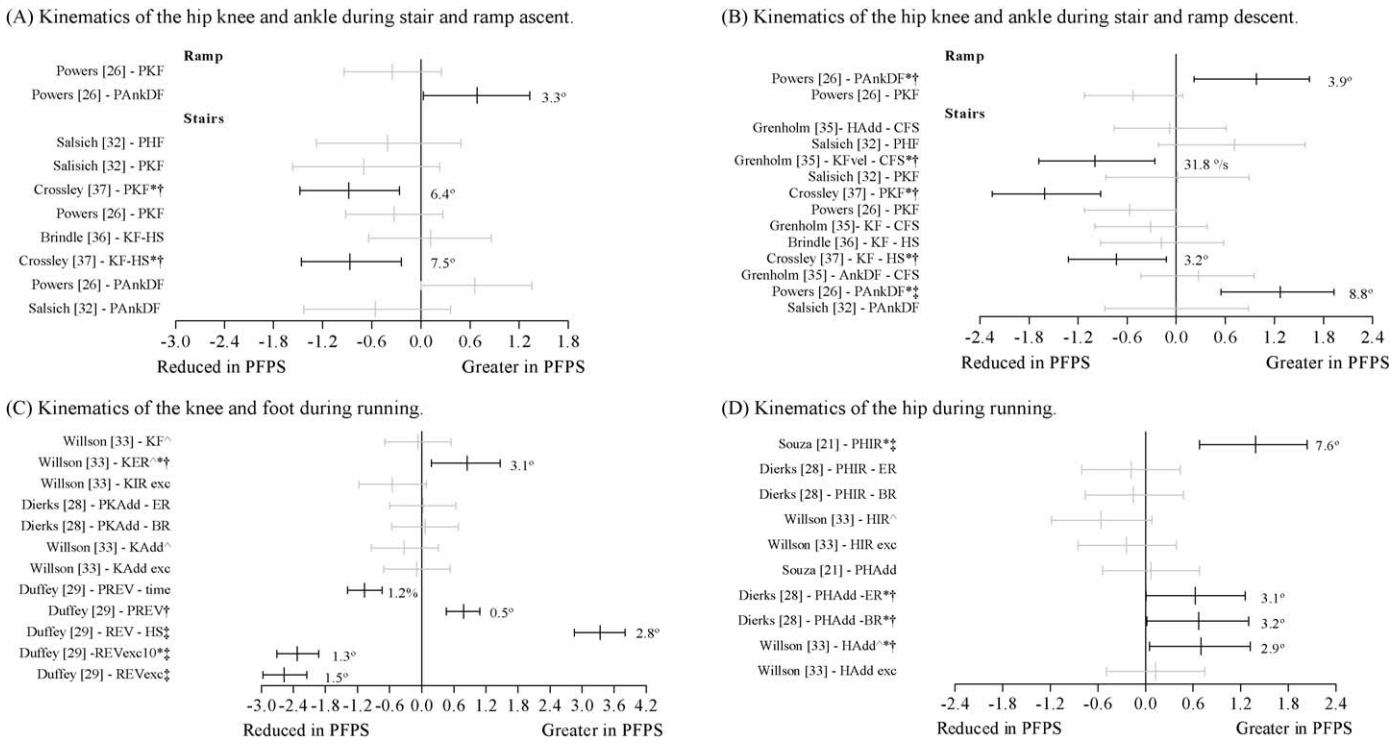

Fig. 3. Kinematics during tasks of increased demand—running, stair negotiation and ramp negotiation (black plots = significant findings with group difference adjacent the right error bar, grey plots = non-significant findings). (A) Kinematics of the hip knee and ankle during stair and ramp ascent. (B) Kinematics of the hip knee and ankle during stair and ramp descent. (C) Kinematics of the knee and foot during running. (D) Kinematics of the hip during running. (*) Variables were reported to have statistically significant differences between groups in original study. (†) Medium effect sizes found. (‡) Large effect sizes found. (^) At peak knee extension moment. *Variable abbreviations*: BR: beginning of run, ER: end of run, CFS: contra-lateral foot strike, PKF: peak knee flexion, KF-HS: knee flexion at heel strike, PHF: peak hip flexion, PAnkDF: peak ankle dorsiflexion, time: timing of, PREV: peak rearfoot eversion, HIR: hip internal rotation, HAdd: hip adduction, HIR exc: hip internal rotation excursion, HAdd exc: hip adduction excursion, KIR exc: knee internal rotation excursion, KAdd exc: knee adduction excursion, KER: knee external rotation, KAdd: knee adduction, KF: knee flexion, REV-HS: rearfoot eversion at heel strike, REVexc10: excursion in first 10% of stance phase, REVexc: excursion.

4.1.4. Meta-analysis, effect size calculation and statistical power

Kinematic gait characteristics evaluated varied greatly between studies included in the review (see Table 5). Heterogeneity of methodology and participant characteristics from included studies in the review made data pooling and meta-analysis inappropriate. Many of the included studies did not report adequate data for effect size calculations for some or all of their measured variables. This led to the exclusion of some data when authors could not be successfully contacted or supply additional data. As a result, studies that may have provided additional insight into kinematic gait characteristics associated with PFPS were excluded. Only six out of 24 included studies contained a minimum of 20 participants in both groups (see Table 4). These low participant numbers may have led to issues with statistical power and potentially resulted in type II errors for many comparisons made [45].

4.2. Case–control findings

4.2.1. Walking kinematics

No studies with adequate data were found which simultaneously evaluated kinematics at the knee, hip and foot/ankle during walking. No significant differences in peaks [27,30] or excursions [39] of rearfoot eversion during walking were indicated by findings included in the review (see Fig. 2A). Limited evidence of delayed peak rearfoot eversion [30,39] and abduction [30] (see Fig. 2A) may indicate the existence of prolonged pronation in individuals with PFPS [8,12]. Greater rearfoot eversion angle was found in a PFPS population at heel strike transient (large effect size) [24], adding further evidence that rearfoot kinematic differences may be associated with PFPS. However, without prospective evaluation it is not possible to determine if these differences are risk factors or compensatory strategies associated with PFPS. The significance of earlier peak rearfoot adduction and dorsiflexion found in one study [30] is unclear without further evaluation of its possible effects on other segments of the foot and more proximal structures.

The relationship between abnormal rearfoot kinematics and kinematics at the knee in individuals with PFPS during walking remains unclear. Of the studies indicating delayed peak rearfoot eversion [30,39], only one [30] also investigated tibial kinematics. Findings indicated no significant differences in peak or timing of peak tibial rotation (see Fig. 2B). Another study included in the review evaluated both pronation of the foot (measured as a single segment) and tibial rotation [27], with findings indicating no differences in foot or tibial kinematics between groups. However, these findings need to be considered with caution due to significant reduction (17%) in gait velocity found in their PFPS group (see Fig. 1A) which may have compensated possible kinematic differences. Studies indicating delayed rearfoot eversion [30,39] did not report significant group differences for gait velocity. Another possible explanation for discrepancies related to kinematics of the foot may be the different kinematic models used. Whilst studies finding significant delays modelled the rearfoot as a single segment [29,30,39], Powers et al. [27], who found no significant differences, modelled the whole foot as a single segment.

Powers et al. [27] was the only study to report adequate data for effect size calculations related to hip kinematic evaluation during walking in individuals with PFPS. Although not significant, this data indicated a trend towards reduced peak and earlier timing of

peak hip internal rotation during walking [27] (see Fig. 2C). As with increased rearfoot eversion at heel strike transient, prospective research is required to determine whether these possible differences are risk factors or compensations associated with PFPS.

In the sagittal plane, significant reductions in knee flexion angle were found at heel strike [31] and during early stance (i.e. at 10% and 20% of gait cycle) [40] during walking (large effect sizes) (see Fig. 2C). This may be a strategy by individuals with PFPS to reduce loading on the PFJ at and following heel strike. Limited evidence indicated no difference in peak knee flexion [23,25,31] or peak knee extension [23] during walking (see Fig. 2C), which would indicate that the range of sagittal plane knee motion may not be altered in individuals with PFPS during walking. Increased peak ankle dorsiflexion (medium effect) during walking was found using a kinematic model which models the foot as a single segment. Therefore, it is not possible to determine if this increased motion occurs at the talocrural joint or other joints in the foot. Further research using more complex foot modelling is required to further clarify these relationships.

4.2.2. Fast walking kinematics

Kinematic evaluation during fast walking was limited to the sagittal plane. Contrary to natural walking, a reduction in peak knee flexion (medium effect) but not knee flexion angle at heel strike was found during fast walking [31] (see Fig. 2D). This contradictory evidence is limited to just one study and therefore requires further investigation. Similar to natural walking, increased peak ankle dorsiflexion was indicated in individuals with PFPS (see Fig. 2D), however, more research is required to determine where in the foot and/or ankle this increased motion occurs.

4.2.3. Stair and ramp negotiation kinematics

Reduced knee flexion velocity during the stance phase of stair descent in individuals with PFPS [35] may be an attempt to minimise loading on the PFJ and avoid pain. Crossley et al. [37] also indicated a possible pain avoidance strategy, with a significant reduction in peak knee flexion and knee flexion at ipsi-lateral foot strike (medium to large effect sizes) in individuals with PFPS found during stair ascent and descent. However, other studies indicated no difference in knee flexion angle at any stance phase gait cycle point evaluated (see Fig. 3B). These discrepant results may have been produced by methodological differences. Whilst Crossley et al. [37] controlled cadence between groups at 96 steps per minute, other studies evaluating knee flexion kinematics during stair negotiation [25,32,35,36] did not. Interestingly, findings from studies which compared cadence between groups indicated reduced cadence during stair negotiation in individuals with PFPS [22,32,35]. Individuals with PFPS in those studies which did not control cadence may have negotiated stairs with reductions in cadence, reversing possible kinematic differences. Considering these methodological discrepancies, further research with and without control of cadence is needed to provide clarity in regards to sagittal plane knee kinematic differences during stair negotiation.

Two studies were found evaluating kinematics of the hip [32,35]. Findings from these indicated no difference in hip flexion/extension during stair ascent or descent [32], and no difference in hip adduction at contra-lateral foot strike [35] (see Fig. 3A and B). Findings from the same studies indicated no significant difference in ankle dorsiflexion during stair ascent [32] or descent [32,35] (see Fig. 3B). However, findings from another study indicated a significant increase in ankle dorsiflexion in a PFPS of 8.8° during stair descent. These limited inconsistent findings require further evaluation using more complex modelling of the foot.

Only one study was found investigating kinematics during ramp negotiation [25], with evaluation limited to peak knee flexion and peak ankle dorsiflexion during ramp ascent and descent (see Fig. 3C). Findings indicated no differences in peak knee flexion but significant increases in peak ankle dorsiflexion during both ascent and descent (medium effect sizes). Again, these possible ankle dorsiflexion differences require further evaluation using more complex modelling of the foot.

4.2.4. Running kinematics

No studies with adequate data were found which simultaneously evaluated kinematics at the knee, hip and foot/ankle during running. Two studies were found evaluating kinematics at the knee during running (see Fig. 3C). Although findings indicated no difference between groups for knee adduction angle at either its peak [28] or peak knee extension moment [33], a greater knee external rotation angle of 3.1° (medium effect) at peak knee extension moment was found [33]. Since, greater knee external rotation (i.e. tibial external rotation relative to the femur) will increase the Q angle and has been reported to alter PFJ contact area in individuals with PFPS [50], this kinematic difference may partially explain aetiology in runners with PFPS.

Only one study was found evaluating kinematic differences at the foot during running [29] (see Fig. 3C). This study contained large participant numbers (>70 in each group) and was of high quality based on both quality assessment scales (see Tables 2 and 3). However, the clinical significance of the small increase in peak rearfoot eversion of 0.5° (medium effect size) is questionable. Small reductions in rearfoot eversion excursion during the first 10% and the total of stance phase of 1.3° and 1.5° respectively (both large effect sizes) were also found. These reductions in range may be the result of the significant increase in rearfoot eversion of 2.8° (large effect size) found at heel strike in the same study. Interestingly, this increase is a similar finding to increased rearfoot eversion at heel strike transient during walking, indicating individuals may strike the ground in greater rearfoot eversion regardless of gait activity. Whether this kinematic difference is a cause or effect relationship associated with PFPS needs to be determined prospectively.

Findings from the three studies evaluating kinematics of the hip during running were equivocal. Greater peak hip adduction but no difference in peak hip internal rotation during running was found in individuals with PFPS in the study by Dierks et al. [28]. Contrary to this, findings from Souza and Powers [21] indicated greater peak hip internal rotation but no difference in peak hip adduction during running in individuals with PFPS. These equivocal findings may be explained by the fact that Souza and Powers [21] evaluated only females, whilst Dierks et al. [28] evaluated both males and females. Interestingly, Dierks et al. [28] reported the presence of different running mechanics at the hip between their male and female participants. Further research with larger participant numbers is needed to make valid comparisons between sexes to confirm if there are different kinematic factors associated with PFPS in males and females. Regardless, both increases in motion are consistent with recent research reports of decreased hip muscle strength (abductors and external rotators) in individuals with PFPS [1,14,15], and may theoretically increase dynamic quadriceps angle and lateral PFJ stress, therefore increasing the risk of PFPS development [2,7,8].

Findings from Willson and Davis [33] are consistent with the greater hip adduction angles found by Dierks et al. [28] during running in individuals with PFPS. However, contrary to Souza and Powers [21], findings from Willson and Davis [33] indicated a trend towards reduced hip internal rotation. This inconsistent finding may result from hip internal rotation being evaluated at different points of the gait cycle in the two studies. Hip internal rotation angle was measured at its peak in the study by Souza and Powers [21], whilst it was measured at peak knee extension moment in the

study by Willson and Davis [33]. Therefore, combining evaluation of these two variables in future research may be needed to provide clarity.

4.3. Limitations

Many possible significant differences in kinematics between groups may not have been detected by previous case–control studies due to low participant numbers and lack of consideration for spatiotemporal gait characteristics. This review did not include non-English papers due to cost and time associated with translation. This may have potentially led to a failure to include all relevant evaluations of kinematic gait characteristics associated with PFPS. We also did not critique included studies related to kinematics based on the quality of the kinematic models used, due to the present lack of validated assessment tools to do so. However, this is an important consideration in the design of future kinematic investigations. The 'Quality Index' used in this review was considered the most relevant published quality assessment scale for evaluating case–control studies. However, many of the items in the checklist were thought to be irrelevant and were omitted which may affect the validity of the overall scale. Many common methodological weaknesses were identified amongst included studies, meaning caution must be taken when considering findings reported in this review. The majority of included findings were also underpowered due to low participant numbers, adding further caution to interpretation.

4.4. Future directions

Prospective research designs investigating kinematic gait characteristics associated with PFPS are needed. Future case–control studies may wish to control or account for potential differences in spatiotemporal gait characteristics. Variability in inclusion/exclusion criteria used amongst included studies highlights the need for consensus in future research investigating kinematic gait characteristics associated with PFPS. To assist this, addressing each of the items from the inclusion/exclusion criteria checklist (see Appendix A) is recommended. To enhance external validity of future research specific to PFPS diagnosis, it is also recommended that the age range be limited between 18 and 40 years of age, producing consistency with clinical trials. Since both male and female individuals develop PFPS, research evaluating both genders with the view of comparing differences between genders should be considered where possible in future investigations. To better understand the relationship between kinematics at the knee, hip and foot and ankle, simultaneous evaluation of the entire kinetic chain during all gait activities is needed.

5. Conclusion

Evidence for kinematic gait characteristic associated with PFPS is currently limited by a paucity of published prospective studies, and methodological weaknesses in existing case–control studies. Prospective evaluation of kinematic gait characteristics in a PFPS population to determine which variables are possible risk factors for the condition is needed. Evaluation of knee, hip and foot and ankle kinematics simultaneously with larger participant numbers, consideration to spatiotemporal gait characteristics, and greater diligence to methodological design is needed in future PFPS kinematic research.

Previous findings from case–control studies must be considered with caution due to methodological weaknesses. However, the available evidence indicates that during walking, individuals with PFPS may exhibit delayed peak rearfoot eversion, increased rearfoot eversion at heel strike transient, and a possible reduction in gait velocity. Additionally, during running, individuals with PFPS may exhibit increased knee external rotation at peak knee extension moment, delayed timing of peak rearfoot eversion, increased rearfoot eversion at heel strike, reduced rearfoot eversion excursion during early and total stance, and greater hip adduction. Inconsistent findings related to hip internal rotation during running indicate the need for further research to provide clarity.

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Conflict of interest

The authors state that there are no conflicts of interest which might have influenced the preparation of this manuscript.

Appendix A. Quality Assessment for inclusion/exclusion criteria

Inclusion:

1. Clear definition of location? ☐
2. Insidious onset unrelated to trauma (including patellar dislocation) ☐
3. Symptoms consistent with PFPS diagnosis (e.g. pain during squatting, kneeling, walking, running, stairs, or sitting with a flexed knee), or positive findings with appropriate clinical tests (e.g. PFJ compression, resisted quadriceps contraction) ☐

Exclusion:

Clearly defined exclusion criteria including:

4. Previous knee surgery ☐
5. Internal derangement ☐
6. Ligamentous instability ☐
7. Other sources of anterior knee pain such as patellar tendonopathy ☐

Total score = /7

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