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Kinematic and Kinetic Gait Characteristics in People with Patellofemoral Pain: A Systematic Review and Meta-analysis

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Abstract

Background:
Patellofemoral pain (PFP) is a prevalent knee condition with many proposed biomechanically orientated etiological factors and treatments.
Objective:
We aimed to systematically review and synthesize the evidence for biomechanical variables (spatiotemporal, kinematic, kinetic) during walking and running in people with PFP compared with pain-free controls, and to determine if biomechanical variables contribute to the development of PFP.
Design:
Systematic review and meta-analysis.
Data sources:
We searched Medline, CINAHL, SPORTDiscus, Embase, and Web of Science from inception to October 2021.
Eligibility criteria for selecting studies:
All study designs (prospective, case–control (± interventional component, provided pre-intervention data were reported for both groups), cross-sectional) comparing spatiotemporal, kinematic, and/or kinetic variables during walking and/or running between people with and without PFP.
Results:
We identified 55 studies involving 1300 people with PFP and 1393 pain-free controls. Overall pooled analysis identified that people with PFP had slower gait velocity [moderate evidence, standardized mean difference (SMD) − 0.50, 95% confidence interval (CI) − 0.72, − 0.27], lower cadence (limited evidence, SMD − 0.43, 95% CI − 0.74 to − 0.12), and shorter stride length (limited evidence, SMD − 0.46, 95% CI − 0.80, − 0.12). People with PFP also had greater peak contralateral pelvic drop (moderate evidence, SMD − 0.46, 95% CI − 0.90, − 0.03), smaller peak knee flexion angles (moderate evidence, SMD − 0.30, 95% CI − 0.52, − 0.08), and smaller peak knee extension moments (limited evidence, SMD − 0.41, 95% CI − 0.75, − 0.07) compared with controls. Females with PFP had greater peak hip flexion (moderate evidence, SMD 0.83, 95% CI 0.30, 1.36) and rearfoot eversion (limited evidence, SMD 0.59, 95% CI 0.03, 1.14) angles compared to pain-free females. No significant between-group differences were identified for all other biomechanical variables and data pooling was not possible for prospective studies.
Conclusion:
A limited number of biomechanical differences exist when comparing people with and without PFP, mostly characterized by small-to-moderate effect sizes. People with PFP ambulate slower, with lower cadence and a shortened stride length, greater contralateral pelvic drop, and lower knee flexion angles and knee extension moments. It is unclear whether these features are present prior to PFP onset or occur as pain-compensatory movement strategies given the lack of prospective data.
Trial Registration:
PROSPERO # CRD42019080241.

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SYSTEMATIC REVIEW

Kinematic and Kinetic Gait Characteristics in People with Patellofemoral Pain: A Systematic Review and Meta-analysis

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Abstract

Background Patellofemoral pain (PFP) is a prevalent knee condition with many proposed biomechanically orientated etiological factors and treatments.

Objective We aimed to systematically review and synthesize the evidence for biomechanical variables (spatiotemporal, kinematic, kinetic) during walking and running in people with PFP compared with pain-free controls, and to determine if biomechanical variables contribute to the development of PFP.

Design Systematic review and meta-analysis.

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Eligibility criteria for selecting studies All study designs (prospective, case–control (± interventional component, provided pre-intervention data were reported for both groups), cross-sectional) comparing spatiotemporal, kinematic, and/or kinetic variables during walking and/or running between people with and without PFP.

Results We identified 55 studies involving 1300 people with PFP and 1393 pain-free controls. Overall pooled analysis identified that people with PFP had slower gait velocity [moderate evidence, standardized mean difference (SMD) − 0.50, 95% confidence interval (CI) − 0.72, − 0.27], lower cadence (limited evidence, SMD − 0.43, 95% CI − 0.74 to − 0.12), and shorter stride length (limited evidence, SMD − 0.46, 95% CI − 0.80, − 0.12). People with PFP also had greater peak contralateral pelvic drop (moderate evidence, SMD − 0.46, 95% CI − 0.90, − 0.03), smaller peak knee flexion angles (moderate evidence, SMD − 0.30, 95% CI − 0.52, − 0.08), and smaller peak knee extension moments (limited evidence, SMD − 0.41, 95% CI − 0.75, − 0.07) compared with controls. Females with PFP had greater peak hip flexion (moderate evidence, SMD 0.83, 95% CI 0.30, 1.36) and rearfoot eversion (limited evidence, SMD 0.59, 95% CI 0.03, 1.14) angles compared to pain-free females. No significant between-group differences were identified for all other biomechanical variables and data pooling was not possible for prospective studies.

Conclusion A limited number of biomechanical differences exist when comparing people with and without PFP, mostly characterized by small-to-moderate effect sizes. People with PFP ambulate slower, with lower cadence and a shortened stride length, greater contralateral pelvic drop, and lower knee flexion angles and knee extension moments. It is unclear whether these features are present prior to PFP onset or occur as pain-compensatory movement strategies given the lack of prospective data.

Trial Registration PROSPERO # CRD42019080241.

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Key Points

People with patellofemoral pain (PFP) walk and run slower and have reduced peak knee flexion angles and knee extension moments.

Females with PFP have greater hip flexion and rearfoot eversion and people with PFP have greater contralateral pelvic drop during running.

People with PFP ambulate with similar hip adduction and internal rotation, and knee abduction kinematics to pain-free controls.

1 Introduction

Patellofemoral pain (PFP) is characterized by peri- and/or retro-patellar pain during loaded knee flexion tasks, including running and walking [1, 2]. PFP is common in adults [3] and adolescents [4, 5], affecting up to 23% of the general population [3–5] and 21% of runners [6]. There is evidence that PFP negatively impacts quality of life and physical activity participation [7, 8], and it has been debated that PFP may be a precursor to patellofemoral osteoarthritis [9, 10].

PFP is associated with many physical and non-physical factors, including biomechanical, psychosocial, and lifestyle factors [1, 11–13]. The role of biomechanics in PFP continues to be debated [14, 15], but it has been proposed to contribute to the development and persistence of PFP in some people [16]. A theoretical pathomechanical model of PFP [16] proposes that excessive loading of the patellofemoral joint (PFJ) leads to increased PFJ contact stress and nociception from the subchondral bone and other surrounding tissues in people with PFP [1]. Supporting this model, elevated PFJ stress has been reported in people with PFP compared with pain-free controls during both walking and running [17, 18]. PFJ stress can increase with small reductions in PFJ contact area, resulting from altered tibial and femoral kinematics in the frontal and transverse planes [16]. There are studies that do not support this model, reporting no difference in joint force/stress between people with and without PFP [19, 20] and demonstrating the importance of continued effort towards understanding of the role of biomechanics in PFP.

A previous systematic review of spatiotemporal and kinematic variables during gait in people with PFP covered literature up until 2009 [21]. This review of 24 case–control studies did not conduct a meta-analysis [21], but did report that hip adduction, knee external rotation, and rearfoot eversion kinematics were altered in people with PFP compared with controls. A more recent systematic review and meta-analysis of 21 running studies searched for in 2015 [22] reported moderate evidence of increased peak hip adduction, hip internal rotation, and contralateral pelvic drop in people with PFP compared with controls. This review also identified inconsistent biomechanical reporting in included studies [22], highlighting the need for reporting guidelines to facilitate methodological homogeneity and scientific replication. Previous systematic reviews of biomechanics associated with PFP have not included subgrouping in their analyses for sex and task, which may provide valuable insight into the association of these factors with PFP.

Given the limitations of previous biomechanics systematic reviews in the field of PFP [21, 22], and the number of studies published since they were conducted, an updated systematic review and meta-analysis is warranted [23]. The primary aim of this systematic review and meta-analysis was to synthesize the evidence for spatiotemporal, kinematic, and kinetic variables during walking and running in people with PFP, or those who develop PFP, compared with pain-free controls. A secondary aim was to summarize the diagnostic and biomechanical reporting in the included studies, to aid in the future development of validated checklists.

2 Methods

2.1 Trial Registration

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement [24, 25] and prospectively registered this systematic review with PROSPERO (Registration no.: CRD42019080241), with few deviations from protocol. During literature searching, we identified several case–control studies with multiple conditions (i.e., an immediate intervention) that included both people with and without PFP, from which we could extract baseline data for analysis, and so we decided to make such studies eligible for inclusion. Our protocol also did not include stair ambulation, which was included in the original study [21] and could be considered another measure of gait. While our registered protocol did not specifically identify the PFP diagnostic checklist, this checklist was part of the procedures in the original study [21].

2.2 Literature Search Strategy

Two health sciences librarians conducted a systematic search from inception to 1 October 2021 (Fig. 1). We duplicated and expanded the search strategy from Barton et al. [21] to identify studies addressing both PFP and biomechanics. We used Medline to devise the initial search strategy with

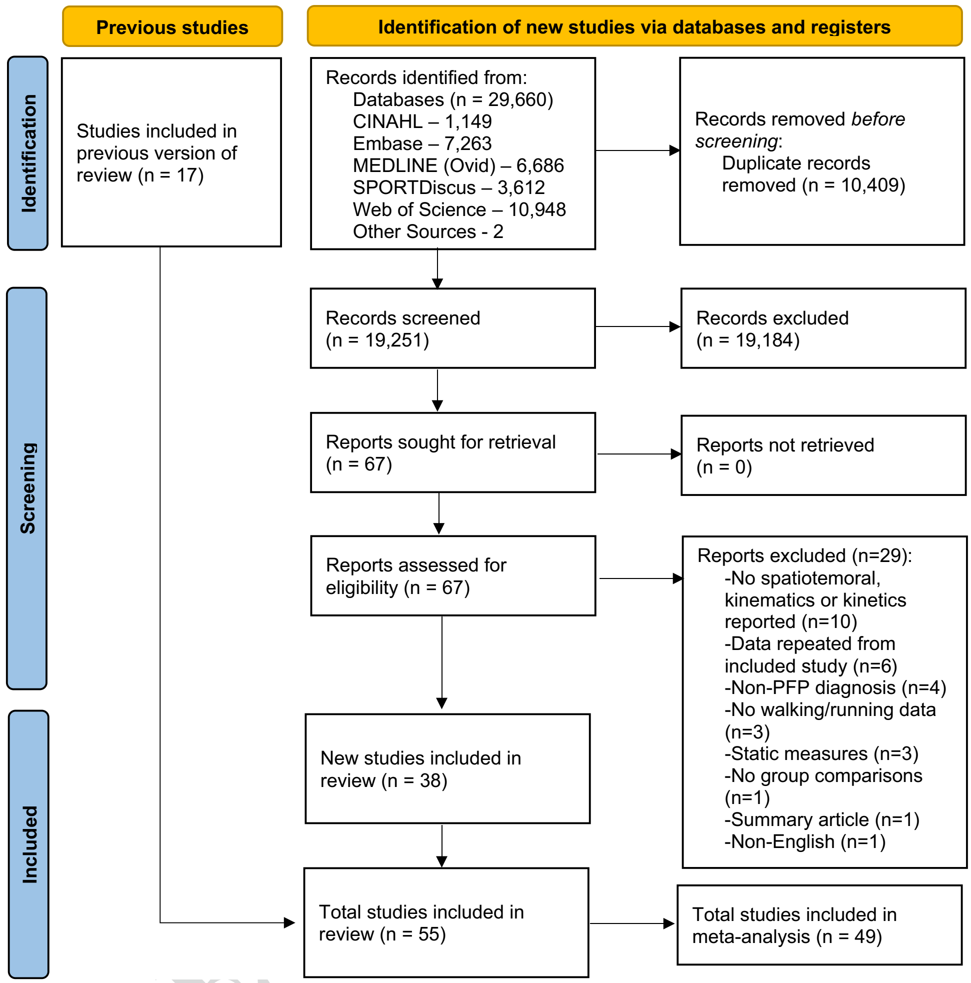

Fig. 1 PRISMA Flow diagram

Medical Subject Headings/controlled vocabulary terms and keywords (Online Resource 1). We also searched CINAHL, SPORTDiscus, Embase, and Web of Science, after considering variations and synonyms. We applied no limits to our search except for the peer reviewed filter in CINAHL and SPORTDiscus. We removed duplicate citations after uploading into EndNote citation management software (X9.1, Clarivate Analytics). One reviewer (DBJ) completed reference checking and citation tracking using Google Scholar.

2.3 Study Selection

Two authors (DBJ, CL) independently screened titles and abstracts for inclusion in EndNote. Articles were included if they were peer reviewed, written in English, and reported biomechanical variables in people with and without PFP. A third author (CB) was available but not required to resolve discrepancies. The same authors independently screened the full texts of all remaining articles. We included prospective ($n = 3$), case–control ($n = 42$), and cross-sectional ($n = 10$) studies if comparisons of biomechanical variables were made between people with and without PFP. Reported baseline data were used in the case of randomized controlled trials.

2.4 Risk of Bias Assessment

We used a modified version of the Newcastle–Ottawa Scale (NOS) [26] to assess the risk of bias of included papers. The NOS has fair to excellent reliability and is a valid measure of risk of bias [27]. We modified both the case–control and prospective cohort scales by making it relevant specifically to PFP in terminology and scaling some questions to be out of two points (Online Resource 2). We used the case–control scale for assessing the baseline measures of case–control studies involving multiple comparisons. The case–control modified NOS scale comprises seven items and provides an overall score out of 12. A score of 9–12 points equated to high quality (HQ), a score of 5–8 points equated to moderate quality (MQ), and a score of 0–4 points equated to low quality (LQ). The cohort modified NOS scale comprises eight items and provides an overall score out of 13. A score of 10–13 points equated to high quality (HQ), a score of 6–9 points equated to moderate quality (MQ), and a score of

0–5 points equated to low quality (LQ). Two assessors (HH, DBJ) independently applied the modified NOS case–control and prospective cohort scales to their respective study designs. We removed identifiable information for each paper prior to appraisal to reduce the potential for assessor bias. Any discrepancies were discussed during a consensus meeting, and a third assessor (CB) was available but not required to resolve discrepancies.

2.5 Quality of Reporting Assessment

We used two separate scales to assess reporting quality of each included study. We used the PFP Diagnosis Checklist [21] to assess the quality of reporting for PFP inclusion and exclusion criteria. This checklist assisted us in determining how similar a study's population was to the currently accepted definition of PFP [1], which could influence the validity of our findings. The scoring of this scale included seven items for a total of seven points and has been used in previous systematic reviews of PFP [15, 28].

We developed a preliminary Biomechanics Reporting Checklist to summarize key variables of data capture and reporting. We developed an initial checklist by consulting the International Society of Biomechanics (ISB) recommendations [29, 30] and screening the methodology of included studies (DBJ), before sending this to three selected biomechanics experts for peer review. Experts were asked to revise items, add items for inclusion, and/or remove items; substantive recommendations were made that led to multiple changes in categories and ratings, at which point a final version was produced. We used the Biomechanics Reporting Checklist (Online Resource 2) to summarize the reporting of equipment (e.g., cameras, marker characteristics, and placement), models (e.g., coordinate systems, segments, joint centres), data collection (e.g., calibration, behavioural elements, sampling rate, reliability/error), and data processing (e.g., filtering, variables/outcome reporting). The Biomechanics Reporting Checklist included 12 items with a maximal score of 15 points, with higher points indicating more comprehensive reporting.

Two assessors independently applied each of the two scales to all included papers (PFP Diagnosis Checklist: NC, DBJ; Biomechanics Reporting Checklist: BN, DBJ). We met and discussed any discrepancies and a third assessor (CB) was available but not needed to resolve discrepancies. We calculated percentage agreement between assessors for each scale to determine inter-rater reliability.

2.6 Data Extraction

One author (DBJ) extracted the number of participants, participant characteristics (e.g., sex, age, anthropometrics), and biomechanical variables (e.g., spatiotemporal characteristics, segment and joint angles, joint moments) for each included study, and a second author (CL) reviewed and confirmed these. When studies included data for both a single sex and mixed-sex groups, we only included the single sex data in the meta-analysis and any duplicate data were excluded. In studies that reported both self-selected and prescribed walking or running velocities, we included the self-selected velocity in the meta-analysis. Duplicate values from the same sample were excluded from the meta-analysis. Where data were not reported within the study, we pursued data either by contacting the corresponding authors or extracting it from figures with graph analysing software (WebPlotDigitizer, version 4.2, https://automeris.io/WebPlotDigitizer).

2.7 Data Analysis

We grouped studies according to the biomechanical variable(s) reported. We entered means, standard deviations (SDs), and sample sizes into Review Manager 5.0 (The Cochrane Collaboration, 2020). For variables that were extracted from two or more studies with methodological homogeneity, we conducted meta-analyses using a random effects model, and calculated standardized mean differences (SMD) with 95% confidence intervals (CIs). We classified SMDs as small (≤ 0.59), medium (0.60–1.19) or large (≥ 1.20) [31]. We conducted separate sub-group analyses for sex (male, female, mixed-sex) and task (running, walking, fast walking, ramp ascent/descent). For the sex analysis, all tasks were combined, and for the task analysis, all sex groups were combined. We considered group differences to be significant at $p \leq 0.05$ and determined statistical heterogeneity using the I^2 statistic ($I^2 \geq 50\%$). Variables reported by a single study were not meta-analysed but were used to formulate evidence-based recommendations.

2.8 Evidence-Based Recommendations

To provide guidance regarding the strength of the evidence, we combined the results from the modified NOS and statistical outcomes, as described by Van Tulder et al. [32]. We assigned the label of *strong evidence* when the pooled results were statistically homogeneous and derived from three or more studies, including a minimum of two HQ studies. We assigned a label of *moderate evidence* when the pooled results were statistically heterogeneous and derived from multiple studies, including at least one HQ study, or when derived from multiple MQ or LQ studies that were statistically homogeneous. We assigned the label of *limited evidence* when the results were derived from one HQ study or multiple MQ or LQ studies that were statistically heterogeneous. *Very limited evidence* was assigned when the results were from one MQ or LQ study.

3 Results

3.1 Search Strategy

We have summarized the identification and selection of included studies in Fig. 1. The initial search identified 29,660 articles, which resulted in 19,251 studies after removing duplicates. We screened titles and abstracts and then evaluated 67 full-text articles for eligibility (Online Resource 3, Supplementary Material (OSM)). Including the 17 studies on walking and running included in the original systematic review, we included a total of 55 studies [17, 33–86] for data synthesis, of which 49 had at least one variable that we were able to include in a meta-analysis [17, 33–41, 43, 44, 46–53, 55–68, 70–78, 80–83, 85].

3.2 Risk of Bias Assessment

Assessment of risk of bias for 52 case–control studies identified two HQ studies [75, 84], 37 MQ studies [17, 33–36, 38–43, 46, 47, 49–51, 53, 55–57, 59, 61, 63–65, 69–73, 77–79, 81–83, 85], and 13 LQ studies [37, 44, 45, 48, 54, 60, 62, 67, 68, 74, 76, 80, 86]. Risk of bias assessment of three prospective cohort studies identified one HQ study [58] and two MQ studies [52, 66]. Mean percentage agreement for the NOS was 95% (range 89–100%), indicating high inter-rater reliability. All disagreements were settled during a consensus meeting between the two reviewers. Item-specific agreement values are presented in Online Resource 4 (OSM).

3.3 Quality of Reporting Assessment

Scores for the PFP Diagnostic Checklist and the Biomechanics Reporting Checklist are presented in Online Resource 4c (OSM) and Table 1, respectively. Median values for the PFP Diagnostic Checklist and Biomechanics Reporting Checklist were 5 out of 7 (range 0–7) and 9 out of 15 (range 1–14), respectively. Mean percentage agreement was 96% (range 92–100%) for the PFP Diagnosis Checklist and 92% (range 78–100%) for the Biomechanics Reporting Checklist, indicating high interrater reliability. All disagreements were settled during a consensus meeting between the two reviewers. Item-specific agreement values are presented in Online Resource 4c (OSM) and Table 1.

3.4 Population Characteristics

Population characteristics for each included study are summarized in Table 2. A total of 1300 people with PFP and 1393 pain-free controls were included across all studies. Within the included PFP groups, studies reported the inclusion of 734 (56.5%) females and 375 (28.8%) males, with sex not reported for 191 (14.7%) participants. Within the pain-free control groups, 584 (41.9%) females and 252 (18.1%) males were reported, with sex not reported for the remaining 554 (40.0%) participants. The mean (± SD) age reported for people with PFP and pain-free control groups was 27.9 ± 4.6 and 27.2 ± 4.3 years, respectively. Population sources were runners (35%), people presenting to an orthopaedic clinic (18%), general population (13%), college-aged (7%), physically active population (5%), adolescents (4%), and military population (2%), with 16% of studies lacking a description of the population source.

3.5 Study Characteristics

Task and biomechanical variable characteristics for each included study are summarized in Table 3. Running (58.2%) was the most common task included, followed by walking (45.5%), fast walking (7.3%), and ramp ascent and descent (7.3%), with 17.3% of studies reporting multiple tasks. Half of the included studies reported at least one spatiotemporal characteristic, including velocity (93.1%), stride length (34.5%), and cadence (44.8%). The frontal plane was the most reported plane of measurement (70%), followed by the sagittal (64%) and transverse (53%) planes; 45%, 34%, and 25% of studies reported data from one, two, or all three planes, respectively. The knee was the most reported joint (74%), followed by the hip (49%) and ankle (30%). The foot/rearfoot (23%) was the most reported segment, followed by the tibia and pelvis (15%), then femur and trunk (11%). Most studies reported kinematic (57%), or both kinematic and kinetic variables (40%), measured primarily by three-dimensional (3D) motion analysis (80%). All reported data are retrospective unless described as prospective ($n = 3$) [52, 58, 66]. Prospective studies were not included in the meta-analysis due to the absence of opportunities for data pooling.

3.6 Spatiotemporal Gait Characteristics

Data were pooled for gait velocity, stride length, and cadence, including subgroup analyses by sex and task. Only significant differences derived through meta-analysis are accompanied by supporting statistics. A summary of spatiotemporal gait characteristic results is provided below, and in the evidence gap map (Fig. 2). Complete results from meta-analyses can be seen in Table 4 and forest plots are provided in Online Resource 5 (OSM).

3.6.1 Gait Velocity

Moderate evidence indicates that gait velocity is lower in people with PFP compared with controls ($I^2 = 72\%$, small significant SMD − 0.50, 95% CI − 0.72, − 0.27).

Table 1 Biomechanics reporting checklist

	Equipment		Model			Data collection				Data processing			Score (15)
	(1) Equipment	(2) Markers	(1) Coordinate systems	(2) Segments	(3) Joint centers	(1) Calibration	(2) Behavioral elements	(3) Sampling rate	(4) Reliability & error	(1) Processing	(2) Variables	(3) Outcome	
Noehren et al. [65]	1	2	1	1	1	1	1	1	2	1	1	1	14
Noehren et al. [66]	1	2	1	1	1	1	1	1	2	1	1	1	14
Bazett-Jones et al. [36]	1	2	1	1	1	1	1	1	0	1	1	1	12
Bramah et al. [39]	1	3	1	1	0	0	1	1	1	1	1	1	12
Levinger and Gilleard [56]	1	2	1	1	1	1	1	1	0	1	1	1	12
Liao et al. [57]	1	2	1	1	1	1	1	1	0	1	1	1	12
Salsich and Long-Rossi [75]	1	3	0	0	0	1	1	1	2	1	1	1	12
Willson et al. [81]	1	2	1	1	1	1	1	1	0	1	1	1	12
Brechter and Powers [17]	1	2	1	1	1	1	1	1	0	0	1	1	11
Callaghan and Baltzopoulos [41]	1	2	1	1	0	0	1	1	2	0	1	1	11
Dierks et al. [44]	1	2	1	1	0	1	1	1	0	1	1	1	11
Dingenen et al. [84]	1	2	0	1	0	0	1	1	2	1	1	1	11
Haghighat et al. [85]	1	2	1	1	0	1	1	1	0	1	1	1	11
Levinger and Gilleard [55]	1	2	1	1	0	1	1	1	0	1	1	1	11
Neal et al. [63]	1	2	0	0	1	1	1	1	2	0	1	1	11

Table 1 (continued)

	Equipment		Model			Data collection				Data processing			Score (15)
	(1) Equipment	(2) Markers	(1) Coordinate systems	(2) Segments	(3) Joint centers	(1) Calibration	(2) Behavioral elements	(3) Sampling rate	(4) Reliability & error	(1) Processing	(2) Variables	(3) Outcome	
Willson and Davis [80]	1	2	1	1	0	1	1	1	0	1	1	1	11
Boldt et al. [38]	1	2	0	0	1	1	1	1	0	1	1	1	10
Chen and Powers [42]	1	2	1	1	0	1	0	1	0	1	1	1	10
Esculier et al. [47]	1	2	1	0	0	1	1	1	0	1	1	1	10
Ferber et al. [48]	1	1	0	0	0	1	1	1	2	1	1	1	10
Heiderscheit et al. [51]	1	2	1	1	0	1	0	1	0	1	1	1	10
Powers et al. [72]	1	2	0	1	0	0	1	1	2	0	1	1	10
Souza and Powers [77]	1	2	0	0	0	1	1	1	2	0	1	1	10
Stefanyshyn et al. [79]	1	1	0	1	1	1	1	1	0	1	1	1	10
Willy et al. [82]	1	1	0	1	1	1	1	1	0	1	1	1	10
Wirtz et al. [83]	1	1	0	1	1	1	1	1	0	1	1	1	10
Barton et al. [34]	1	3	0	0	0	1	1	1	0	0	1	1	9
Barton et al. [35]	1	3	0	0	0	1	1	1	0	0	1	1	9
Burston et al. [40]	1	1	1	0	1	0	1	1	0	1	1	1	9
Fox et al. [49]	1	2	0	0	0	1	1	1	0	1	1	1	9
Luz et al. [58]	1	1	1	0	0	1	1	1	0	1	1	1	9
Pelletier et al. [68]	1	2	0	0	0	1	1	1	0	1	1	1	9

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Table 1 (continued)

	Equipment		Model			Data collection				Data processing			Score (15)
	(1) Equipment	(2) Markers	(1) Coordinate systems	(2) Segments	(3) Joint centers	(1) Calibration	(2) Behavioral elements	(3) Sampling rate	(4) Reliability & error	(1) Processing	(2) Variables	(3) Outcome	
Rodrigues et al. [74]	1	1	0	1	0	1	1	1	0	1	1	1	9
Noehren et al. [64]	1	1	0	0	0	1	1	1	0	1	1	1	8
Souza and Powers [78]	1	2	0	0	0	1	1	1	0	0	1	1	8
Besier et al. [37]	1	1	0	0	0	1	0	1	0	1	1	1	7
Kedroff et al. [53]	1	1	1	1	0	0	1	1	1	0	0	0	7
Powers et al. [71]	1	1	0	0	0	0	0	1	1	1	1	1	7
Rees et al. [73]	1	0	0	0	0	0	1	1	1	1	1	1	7
Freddolini et al. [50]	1	1	0	0	0	1	1	1	0	0	1	0	6
Hetsroni et al. [52]	1	2	0	1	0	0	0	1	0	0	1	0	6
Moss et al. [61]	1	1	0	0	0	0	1	1	0	0	1	1	6
Nadeau et al. [62]	1	1	0	0	0	0	1	1	0	1	0	1	6
Assa et al. [33]	1	0	0	0	0	0	1	0	1	0	1	1	5
Claudon et al. [43]	1	1	0	0	0	0	0	1	0	0	1	1	5
Duffey et al. [46]	1	1	0	0	0	0	1	1	0	1	0	0	5
Luedke et al. [58]	1	0	0	0	0	0	1	0	1	0	1	1	5
Messier et al. [60]	1	1	0	0	0	0	0	1	0	1	1	0	5
Paoloni et al. [67]	1	0	0	0	0	0	1	1	0	0	1	1	5
Powers et al. [70]	1	1	0	0	0	0	0	1	0	1	0	1	5

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Table 1 (continued)

	Equipment		Model			Data collection				Data processing			Score (15)
	(1) Equipment	(2) Markers	(1) Coordinate systems	(2) Segments	(3) Joint centers	(1) Calibration	(2) Behavioral elements	(3) Sampling rate	(4) Reliability & error	(1) Processing	(2) Variables	(3) Outcome	
Altukhova et al. [86]	1	2	0	0	0	0	0	0	0	0	0	1	4
Dillon et al. [45]	0	0	0	0	0	0	0	0	2	0	1	1	4
Powers et al. [69]	1	1	0	0	0	0	0	1	0	0	0	0	3
Santos et al. [76]	1	0	0	0	0	0	0	0	0	0	1	0	2
Kim et al. [54]	1	0	0	0	0	0	0	0	0	0	0	0	1
Agreement	96%	78%	84%	96%	100%	98%	89%	98%	95%	84%	96%	89%	38%

Sex: Gait velocity is lower in mixed-sex cohorts (moderate evidence, $I^2 = 0\%$, small significant SMD − 0.23, 95% CI − 0.40, − 0.06) and females (moderate evidence, $I^2 = 78\%$, medium significant SMD − 0.64, 95% CI − 1.04, − 0.25) with PFP compared with controls. There is no difference in gait velocity for males with PFP and pain-free males (limited evidence).

Task: Gait velocity is lower in people with PFP during walking (moderate evidence, $I^2 = 69\%$, small significant SMD − 0.38, 95% CI − 0.68, − 0.08), running (limited evidence, $I^2 = 59\%$, small significant SMD − 0.40, 95% CI − 0.74, − 0.06), and ramp ascent and descent (very limited evidence) compared with controls. There is no difference in gait velocity in people with PFP during fast walking compared with controls (moderate evidence).

3.6.2 Cadence

Limited evidence indicates no prospective association between cadence and high school runners who subsequently developed PFP.

Limited evidence indicates that cadence is lower in people with PFP compared with controls ($I^2 = 72\%$, small significant SMD − 0.43, 95% CI − 0.74, − 0.12).

Sex: Cadence is lower in females with PFP compared with pain-free females (limited evidence, $I^2 = 74\%$, medium significant SMD − 0.75, 95% CI − 1.20, − 0.31). Cadence in males and mixed-sex cohorts with PFP is no different to controls (limited and moderate evidence, respectively).

Task: Cadence in people with PFP is no different to controls during running (limited evidence), walking (limited evidence), or fast walking (moderate evidence). Cadence is lower in people with PFP during ramp descent and ascent compared with controls (very limited evidence).

3.6.3 Stride Length

Limited evidence indicates that stride length in people with PFP is shorter compared with controls ($I^2 = 72\%$, small significant SMD − 0.46, 95% CI − 0.80, − 0.12).

Sex: When sub-grouped by sex (females, males, mixed-sex groups), people with PFP are no different to controls in stride length (limited evidence).

Task: When compared with controls, people with PFP ambulate with a shorter stride length during walking (limited evidence; $I^2 = 65\%$, small significant SMD − 0.44, 95% CI − 0.82, − 0.06) and during ramp descent and ascent (very limited evidence). Stride length for people with PFP is not different to controls during running (moderate evidence) or fast walking (limited evidence).

Table 2 Sample sizes and population characteristics from each included paper

Paper	Sample size (M,F)		Age range (mean age)		Mass (kg), height (cm), (BMI; kg/m^2)	
	PFP	Control	PFP	Control	PFP	Control
Altukhova et al. [86]	35 (15,20)	20 (14,6)	22–67 (33.6)	NR (29.7)	NR, NR (NR)	NR, NR (NR)
Assa et al. [33]	157 (91,66)	31 (17,14)	NR (30.3)	NR (31.9)	70.5, 172 (23.6)	67.5, 173 (22.5)
Barton et al. [34]	26 (5,21)	20 (4,16)	18–35 (25.1)	18–35 (23.4)	66.7, 168.6 (NR)	66.0, 171.1 (NR)
Barton et al. [35][a]	26 (5,21)	20 (4,16)	18–35 (25)	18–35 (23)	67, 169 (NR)	66, 171 (NR)
Bazett-Jones et al. [36]	19 (10,9)	19 (10,9)	18–40 (26.0)	18–40 (24.3)	77.3, 174 (NR)	70.2, 174 (NR)
Besier et al. [37]	27 (11,16)	16 (8,8)	M: NR (30.5)	M: NR (27.2)	M: 72.4, 178 (NR)	M: 74.2, 179 (NR)
			F: NR (28.7)	F: NR (28.8)	F: 62.7, 168 (NR)	F: 58.3, 166 (NR)
Boldt et al. [38]	20 (0,20)	20 (0,20)	18–35 (21.3)	18–35 (21.6)	62.9, 168 (NR)	62.1, 169 (NR)
Bramah et al. [39]	18 (NR)	36 (NR)	NR (34.5)	NR (33.2)	64.4, 173.5 (21.3)	60.8, 171.6 (20.6)
Brechter and Powers [17]	10 (5,5)	10 (5,5)	NR (37.1)	NR (32.0)	70.8, 167.9 (NR)	67.9, 167.2 (NR)
			M: NR (38.2)	M: NR (32.2)	M: 78.1, 178.9 (NR)	M: 78.1, 177.7 (NR)
			F: NR (36.0)	F: NR (31.8)	F: 63.4, 166.1 (NR)	F: 57.6, 163 (NR)
Burston et al. [40]	15 (8,7)	15 (7,8)	NR (28.6)	NR (30.1)	NR, NR (NR)	NR, NR (NR)
Callaghan and Baltzopoulos [41]	15 (0,15)	15 (0,15)	18–65 (27)	18–65 (23.5)	61.5, NR (NR)	59.7, NR (NR)
Chen and Powers [42]	20 (0,20)	20 (0,20)	18–45 (27.9)	18–45 (26.1)	62.4, 168.1 (NR)	59.1, 165.3 (NR)
Claudon et al. [43]	23 (11,12)	22 (10,12)	NR (32.5)	NR (24.9)	75.6, 172 (25.6)	66.4, 173 (22.2)
Dierks et al. [44]	20 (5,15)	20 (5,15)	18–45 (24.1)	18–45 (22.7)	65.8, 171 (NR)	63.0, 170 (NR)
Dillon et al. [45]	8 (0,8)	11 (0,8)	NR (NR)	NR (NR)	NR, NR (NR)	NR, NR (NR)
Dingenen et al. [84]	5 (NR)	24 (7,17)	NR (NR)	NR (29.6)	NR, NR (NR)	66.0, 172.1 (22.1)
Duffey et al. [46]	99 (69,30)	70 (53,27)	NR (36.0)	NR (35.0)	69.5, 172.1 (23.3)	70.2, 174.5 (22.9)
Esculier et al. [47]	21 (5,16)	20 (5,15)	18–45 (34.1)	18–45 (33.2)	67.4, 167.8 (NR)	62.8, 169.1 (NR)
Ferber et al. [48]	15 (5,10)	10 (4,6)	NR (35.2)	NR (29.9)	69.1, 165 (NR)	73.1, 173 (NR)
Fox et al. (Acute) [49]	25 (11,14)	98	NR (30.0)	NR (39.4)	66.1, 172.2 (NR)	69.4, 171.0 (NR)
Fox et al. (Chronic) [49]	73 (28,45)		NR (32.5)		67.6, 171.2 (NR)	
Freddolini et al. [50]	40 (40,0)	40 (40,0)	NR (22.5)	NR (19.2)	67.0, 173 (NR)	64.3, 171 (NR)
Haghighat et al. [85]	17 (0,17)	17 (0,17)	18–35 (25.9)	18–35 (24.1)	59.7, 163 (NR)	56.4, 161 (NR)
Heiderscheit et al. [51]	8 (0,8)	8 (0,8)	19–36 (24)	21–38 (27)	70.1, 171.0 (NR)	57.9, 170.0 (NR)
Hetsroni et al. [52]	61 (NR)	344 (NR)	NR (NR)	NR (NR)	NR, NR (NR)	NR, NR (NR)
Kedroff et al. [53]	11 (6,5)	11 (6,5)	18–45 (23.7)	18–45 (25.0)	69.6, 170 (NR)	67.6, 170 (NR)
Kim et al. [54]	32 (0,32)	25 (0,25)	NR (21.6)	NR (21.1)	52.8, 162.7 (NR)	52.7, 161.5 (NR)
Levinger and Gilleard [55]	11 (0,11)	14 (0,14)	NR (36.3)	NR (25.1)	64.9, 166.1 (NR)	61.3, 166.3 (NR)
Levinger and Gilleard [56]	13 (0,13)	14 (0,14)	NR (38.4)	NR (25.1)	70.6, 166.3 (NR)	61.3, 166.3 (NR)
Liao et al. [57]	12 (0,12)	10 (0,10)	NR (27.6)	NR (27.4)	54.6, 160 (NR)	58.8, 160 (NR)
Luedke et al. [58]	NR (NR)	NR (NR)	NR (NR)	NR (NR)	NR, NR (NR)	NR, NR (NR)
Luz et al. [59]	27 (16,11)	27 (16,11)	18–35 (27)	18–35 (26)	71.2, 172 (23.89)	72.5, 174 (23.75)
Messier et al. [60]	16 (12,4)	20 (14,6)	16–50 (NR)	16–50 (NR)	NR, NR (NR)	NR, NR (NR)
Moss et al. [61]	14 (NR)	15 (NR)	NR (NR)	NR (NR)	62, NR (NR)	52, NR (NR)
Nadeau et al. [62]	5 (2,3)	5 (2,3)	NR (28.4)	NR (25.5)	67.6, 172 (NR)	67.0, 170 (NR)
Neal et al. [63]	20 (9,11)	20 (9,11)	18–45 (NR)	18–45 (NR)	NR, NR (NR)	NR, NR (NR)
			M: 18–45 (31.8)	M: 18–45 (28.7)	M: 74.2, 179.8 (NR)	M: 73.2, 177.5 (NR)
			F: 18–45 (29.4)	F: 18–45 (32.4)	F: 56.8, 153.9 (NR)	F: 59.5, 167.1 (NR)
Noehren et al. [64]	15 (0,15)	15 (0,15)	18–45 (27)	18–45 (25)	57.4, 164 (NR)	57.9, 164 (NR)
Noehren et al. [65]	16 (0,16)	16 (0,16)	18–45 (27)	18–45 (25)	57.4, 164 (NR)	58.7, 165 (NR)
Noehren et al. [66]	15 (NR)	NR (NR)	18–45 (27)	18–45 (27)	NR, 165 (NR)	NR, 165 (NR)
Paoloni et al. [67]	9 (2,7)	9 (2,7)	19–45 (28.1)	21–38 (28.3)	64.4, 171 (NR)	64.2, 170 (NR)
Pelletier et al. [68]	12 (NR)	20 (NR)	NR (NR)	NR (NR)	NR, NR (NR)	NR, NR (NR)
			M: NR (30)	M: NR (26.1)	M: 80.3, 180.7 (NR)	M: 76.5, 181.7 (NR)
			F: NR (27.6)	F: NR (23.3)	F: 64.6, 169.6 (NR)	F: 63.5, 172.4 (NR)

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Table 2 (continued)

Paper	Sample size (M,F)		Age range (mean age)		Mass (kg), height (cm), (BMI; kg/m^2)	
	PFP	Control	PFP	Control	PFP	Control
Powers et al. [69]	26 (0,26)	19 (0,19)	14–46 (25.6)	23–38 (27.5)	63.9, 165.1 (NR)	59.2, 165.3 (NR)
Powers et al. [70]	19 (0,19)	19 (0,19)	14–46 (24.4)	23–38 (27.5)	62.4, 165.1 (NR)	59.2, 165.3 (NR)
Powers et al. [71]	15 (0,15)	10 (0,10)	14–41 (26.5)	27–37 (31.5)	65.3, 164.3 (NR)	63.7, 170.9 (NR)
Powers et al. [72]	24 (0,24)	18 (0,18)	15–47 (25.4)	15–47 (27.6)	63.6, 164.9 (NR)	59.6, 165.8 (NR)
Rees et al. [73]	16 (5,11)	16 (5,11)	NR (32.4)	NR (31.7)	65.6, 171.7 (NR)	65.5, 171.1 (NR)
Rodrigues et al. [74]	17 (4,13)	19 (9,10)	NR (29.8)	NR (34.0)	60.2, 163 (NR)	65.2, 172 (NR)
Salsich and Long-Rossi [75]	20 (0,20)	20 (0,20)	18–40 (25.6)	18–40 (24.0)	62.3, 163.0 (NR)	66.1, 165.7 (NR)
Santos et al. [76]	12 (0,12)	15 (0,15)	NR (21)	NR (22)	52.81, 163 (NR)	57.76, 164 (NR)
Souza and Powers [77]	19 (0,19)	19 (0,19)	NR (27)	NR (26)	64.7, 169 (NR)	62.9, 168 (NR)
Souza and Powers [78]	21 (0,21)	20 (0,20)	18–45 (27)	18–45 (26)	64.7, 170 (NR)	62.9, 170 (NR)
Stefanyshyn et al. [79]	20 (NR)	20 (NR)	20–50 (34.6)	20–50 (34.4)	66.8, 170.0 (NR)	70.8, 176.5 (NR)
Willson and Davis [80]	20 (0,20)	20 (0,20)	18–35 (23.3)	18–35 (23.7)	61.7, 166.0 (NR)	61.1, 166 (NR)
Willson et al. [81]	10 (NR)	13 (NR)	18–35 (20.8)	18–35 (21.0)	62.5, 169 (NR)	61.2, 170 (NR)
Willy et al. [82]	36 (NR)	18 (NR)	M: 18–40 (24.7) F: 18–40 (22.2)	M: 18–40 (23.4)	M: NR, NR (25.7) F: NR, NR (21.8)	M: NR, NR (23.4)
Wirtz et al. [83]	20 (0,20)	20 (0,20)	18–35 (21.3)	18–35 (21.6)	62.9, 170 (22.1)	61.8, 170 (21.7)

BMI body mass index, *F* females, *M* males, *NR* not reported, *PFP* patellofemoral pain

[a]Repeated participants from Barton 2011 (only new data were included in analyses)

3.7 Kinematics

Data were pooled for variables at the trunk, pelvis, hip, knee, and foot, and included subgroup analyses by sex and task when appropriate. Only significant differences derived through meta-analysis are accompanied by supporting statistics. A summary of kinematic results is provided below, and in the evidence gap map (Fig. 2). Complete results from meta-analyses can be seen in Table 5 and forest plots are provided in Online Resource 6 (OSM).

3.7.1 Trunk Flexion Angle

Limited evidence indicates that peak trunk flexion angle in people with PFP is not different to controls.

Task: There is no difference in peak trunk flexion angle between people with PFP and controls during running (limited evidence). People with PFP walk with an increased peak trunk flexion angle compared with controls (very limited evidence).

3.7.2 Contralateral Trunk Flexion Angle

Moderate evidence indicates that peak contralateral trunk flexion in people with PFP is no different compared with controls.

Sex: There is no difference in peak contralateral trunk lean in mixed-sex groups and females with PFP compared with controls (moderate evidence).

3.7.3 Anterior Pelvic Tilt Angle

Moderate evidence indicates that peak anterior pelvic tilt in people with PFP is no different compared with controls.

Sex: There is no difference in peak anterior pelvic tiled in mixed-sex groups and females with PFP compared with controls (very limited evidence).

3.7.4 Contralateral Pelvic Drop Angle

There is moderate evidence that peak contralateral pelvic drop is greater in people with PFP compared to controls ($I^2 = 62\%$, small significant SMD − 0.46, 95% CI − 0.90, − 0.03).

Sex: There is no difference in contralateral pelvic drop in females (moderate evidence) or mixed-sex cohorts (moderate evidence) with PFP and controls. Males with PFP have greater contralateral pelvic drop than pain-free males (very limited evidence).

3.7.5 Hip Flexion Angle

Limited evidence indicates that peak hip flexion in people with PFP is not different to controls.

Sex: Moderate evidence indicates that peak hip flexion in females with PFP is greater than pain-free females ($I^2 = 0\%$, medium significant SMD 0.83, 95% CI 0.30, 1.36). There

Table 3 Population sources, tasks, and biomechanical variables in studies of gait in people with and without patellofemoral pain

Paper	Population source (PFP)	Locomotion tasks	Variables measured					Gait characteristics
			Spatiotemporal characteristics	Planes	Joints	Kinematics/kinetics	2D/3D	
Altukhova et al. [86]	Undefined	Walking	None	S	Knee, Hip	Kinematics	IMU	U[a]
Assa et al. [33]	Orthopaedic clinic presentation	Walking	Velocity, SL, Cadence	NA	NA	NA	NA	U[b]
Barton et al. [34]	College-age	Walking	Velocity	S, F, T	Foot, Ankle, Knee, Hip	Kinematics	3D	U
Barton et al. [35]	College-age	Walking	Velocity	F, T	Tibia	Kinematics	3D	U
Bazett-Jones et al. [36]	College-age	Running	None	S, F, T	Knee, Hip, Pelvis, Trunk	Both	3D	C (4.0 ± 0.5 m/s)
Besier et al. [37]	Undefined	Walking, Running	Velocity, SL, Cadence	S	Ankle, Knee, Hip	Both	3D	U
Boldt et al. [38]	Runners (≥ 10 miles/week)	Running	None	F, T	Knee, Hip	Both	3D	C (3.52–3.89 m/s)
Bramah et al. [39]	Runners	Running	None	S, F	Ankle, Knee, Hip, Pelvis, Trunk	Kinematics	3D	C (3.2 m/s)
Brechter and Powers [17]	Orthopaedic clinic presentation	Walking, Fast Walking	Velocity, SL, Cadence	S	Knee	Both	3D	U
Burston et al. [40]	General population (university staff and students)	Walking, Step Descent Task	Velocity	S, F, T	Knee	Both	3D	U
Callaghan and Baltzopoulos [41]	Orthopaedic clinic presentation	Walking	None	F	Rearfoot	Kinematics	2D	U[a]
Chen and Powers [42]	Orthopaedic clinic presentation	Walking, Running	None	S	Knee	Kinetics	3D	U
Claudon et al. [43]	Orthopaedic clinic presentation	Walking	Velocity	S	Knee, Trunk	Both	3D	U[a]
Dierks et al. [44]	Recreational runners (> 15 km/week)	Running (Treadmill)	Velocity	F, T	Knee, Hip	Kinematics	3D	U
Dillon et al. [45]	College-age	Walking, Decline Walking (Treadmill)	None	S, T	Ankle, Tibia, Knee, Femur, Pelvis	Kinematics	2D	C (1.11 m/s)
Dingenen et al. [84]	Recreational runners (> 10 km/week)	Running (Treadmill)	Velocity	S, F	Ankle, Knee, Hip, Pelvis, Trunk	Kinematics	2D	U
Duffey et al. [46]	Recreational and competitive runners (≥ 10 miles/week)	Running	None	F	Rearfoot	Both	2D	U[b]
Esculier et al. [47]	Recreational runners (> 15 km/week)	Running (Treadmill)	Velocity, Cadence	F, T	Hip, Pelvis	Both	3D	U

Table 3 (continued)

Paper	Population source (PFP)	Locomotion tasks	Variables measured					Gait characteristics
			Spatiotemporal characteristics	Planes	Joints	Kinematics/kinetics	2D/3D	
Ferber et al. [48]	Recreational athletes (running > 30 min/day, 3 day/week)	Running (Treadmill)	None	F	Knee	Kinematics	2D	C (2.55 m/s)
Fox et al. [49]	Recreational athletes (running > 30 min/day, 3 day/week)	Running (Treadmill)	Velocity	S, F, T	Ankle, Knee, Hip	Kinematics	3D	U[a]
Freddolini et al. [50]	Undefined	Walking	Velocity, SL, Cadence	S	Knee	Kinematics	3D	U[b]
Haghighat et al. [85]	General population	Running (Treadmill)	Velocity	S, F, T	Ankle, Knee, Hip, Pelvis, Trunk	Kinematics	3D	U
Heiderscheit et al. [51]	General population	Running	SL	S, F	Ankle, Tibia, Femur	Kinematics	3D	C (2.68 m/s)
Hetsroni et al. [52]	Military recruits	Walking (Treadmill)	None	F	Rearfoot	Kinematics	2D	C (5 km/h)
Kedroff et al. [53]	General population (university staff and students)	Walking	Cadence	S, F, T	Foot, Ankle, Tibia, Knee, Hip	Kinematics	3D	U
Kim et al. [54]	General population	Walking	None	T	Foot	Kinematics	U	C (3.5 km/h)
Levinger and Gilleard [55]	Undefined	Walking	Velocity	F	Rearfoot	Kinematics	3D	U
Levinger and Gilleard [56]	Undefined	Walking	Velocity	S, F, T	Rearfoot, Tibia	Kinematics	3D	U
Liao et al. [57]	Recreational runners (> 16 km/week)	Running	None	S, F, T	Knee	Both	3D	C (2.7 m/s)
Luedke et al. [58]	High school runners	Running	Velocity, Cadence	NA	NA	NA	NA	C (3.3 m/s)
Luz et al. [59]	Recreational runners (> 15 km/week)	Running	Velocity	F, T	Rearfoot, Tibia, Femur	Both	3D	U
Messier et al. [60]	Recreational runners (> 4 day/week)	Running	None	S, F	Ankle, Knee	Both	2D	U[a]
Moss et al. [61]	High school athletes	Running	None	F	Rearfoot	Kinematics	2D	U
Nadeau et al. [62]	Orthopaedic clinic presentation	Walking	Velocity, SL, Cadence	S	Ankle, Knee, Hip	Both	2D	U
Neal et al. [63]	Recreational runners (> 10 km/week)	Running	Cadence	F, T	Hip, Knee	Kinematics	3D	U
Noehren et al. [64]	Recreational runners (> 16 km/week)	Running	Velocity	F, T	Hip, Knee	Kinematics	3D	C (3.22 m/s)

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Table 3 (continued)

Paper	Population source (PFP)	Locomotion tasks	Variables measured					Gait characteristics
			Spatiotemporal characteristics	Planes	Joints	Kinematics/kinetics	2D/3D	
Noehren et al. [65]	Recreational runners (> 16 km/week)	Running	None	S, F, T	Foot, Ankle, Hip, Pelvis, Trunk	Kinematics	3D	U[a]
Noehren et al. [66]	Runners (> 32 km/week)	Running	None	F, T	Ankle, Hip	Kinematics	3D	C (3.7 m/s)
Paoloni et al. [67]	Undefined	Walking	Velocity	S, F, T	Knee, Hip	Both	3D	U[b]
Pelletier et al. [68]	Runners (> 30 min/day for > 3 days/week)	Running	None	S, F, T	Knee, Hip	Kinematics	3D	C (3.22 m/s)
Powers et al. [69]	General population (orthopaedic clinic presentation)	Walking, Fast Walking, Ramp Ascent & Descent	None	S	Knee	Kinematics	3D	U[a]
Powers et al. [70]	Orthopaedic clinic presentation	Walking, Fast Walking, Ramp Ascent & Descent	Velocity, SL, Cadence	S	Ankle, Knee, Hip	Kinematics	3D	U[b]
Powers et al. [71]	General population	Walking, Fast Walking	Velocity, SL, Cadence	S	Knee	Kinematics	3D	U[b]
Powers et al. [72]	Undefined	Walking	Velocity, SL, Cadence	T	Foot, Tibia, Femur	Kinematics	3D	U[b]
Rees et al. [73]	General population	Running	Velocity	F	Knee	Kinematics	2D	U[a]
Rodrigues et al. [74]	Recreational runners (> 13 km/week)	Running	None	F, T	Ankle, Tibia, Knee	Kinematics	3D	C (2.9 m/s)
Salsich and Long-Rossi [75]	Undefined	Walking	Velocity	F, T	Knee, Hip	Both	3D	U
Santos et al. [76]	Undefined	Walking, Inclined Walking	Velocity	S	Knee	Both	U	U
Souza and Powers [77]	General population (orthopaedic clinic presentation)	Running	None	S, F	Femur	Both	3D	C (3.0 m/s)
Souza and Powers [78]	General population (orthopaedic clinic presentation)	Running	None	F,T	Hip	Both	3D	C (3.0 m/s)
Stefanyshyn et al. [79]	General population (sports medicine clinic presentation)	Running	None	F	Knee	Kinetics	3D	C (4.0 ± 0.2 m/s)
Willson and Davis [80]	Active females (regular sports participation)	Running	None	S, F, T	Knee, Hip	Both	3D	C (3.7 m/s)

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Table 3 (continued)

Paper	Population source (PFP)	Locomotion tasks	Variables measured					Gait characteristics
			Spatiotemporal characteristics	Planes	Joints	Kinematics/kinetics	2D/3D	
Willson et al. [81]	Recreational runners (> 16 km/week)	Running	None	S	Knee	Both	3D	C (3.7 m/s)
Willy et al. [82]	Recreational runners (> 10 km/week)	Running	None	S, F, T	Knee, Hip, Pelvis	Both	3D	C (3.35 m/s)
Wirtz et al. [83]	Recreational runners (> 16 km/week)	Running	None	S, T	Knee, Hip	Both	3D	C (3.52–3.89 m/s)

2D two-dimensional motion analysis, *3D* three-dimensional motion analysis, *C* controlled, *IMU* inertial measurement unit, *F* frontal, *S* sagittal, *T* transverse, *SL* stride length, *U* uncontrolled and unaccounted for, *PFP* patellofemoral pain

[a]Not reported

[b]Significant differences found

were no differences in peak hip flexion angle between males with PFP and pain-free males (moderate evidence) or mixed-sex PFP and control groups (limited evidence).

Task: Peak hip flexion angle in people with PFP is not different to controls during running (limited evidence) or walking (very limited evidence).

3.7.6 Hip Adduction Angle

Very limited evidence indicates a prospective association between peak hip adduction angle and runners who subsequently develop PFP.

Moderate evidence indicates that peak hip adduction in people with PFP is not different to controls.

Sex: Peak hip adduction is not different in females, males, or mixed-sex groups with PFP compared to controls (moderate evidence).

Task: Peak hip adduction in people with PFP is not different to controls during running (moderate evidence), walking (moderate evidence), or fast walking (limited evidence).

3.7.7 Hip Internal Rotation Angle

Very limited evidence indicates no prospective association between peak hip internal rotation angle and runners who subsequently develop PFP.

Moderate evidence indicates that peak hip internal rotation in people with PFP is not different to controls.

Sex: Peak hip internal rotation is not different in females (moderate evidence), males (moderate evidence), or mixed-sex groups (limited evidence) with PFP compared with controls.

Task: Peak hip internal rotation in people with PFP is not different to controls during walking (moderate evidence), running (limited evidence), or fast walking (limited evidence).

3.7.8 Knee Flexion Angle

Moderate evidence indicates that peak knee flexion angle is smaller in people with PFP compared with controls ($I^2 = 51\%$, small significant SMD − 0.30, 95% CI − 0.52, − 0.08).

Sex: Peak knee flexion angle is smaller in mixed-sex groups with PFP than controls (moderate evidence; $I^2 = 0\%$, small significant SMD − 0.41, 95% CI − 0.64, − 0.18). Peak knee flexion angle is not different in females (moderate evidence) or males (limited evidence) with PFP compared with pain-free females and males.

Task: Peak knee flexion angle in people with PFP is not different to controls during running (moderate evidence), walking (limited evidence) or fast walking (very limited evidence).

3.7.9 Knee Abduction Angle

Moderate evidence indicates that peak knee abduction angle in people with PFP is not different to controls.

Sex: Peak knee abduction angle in mixed-sex groups (limited evidence) and females (limited evidence) with PFP is not different to controls.

Task: Peak knee abduction angle in people with PFP is not different to controls during walking (moderate evidence),

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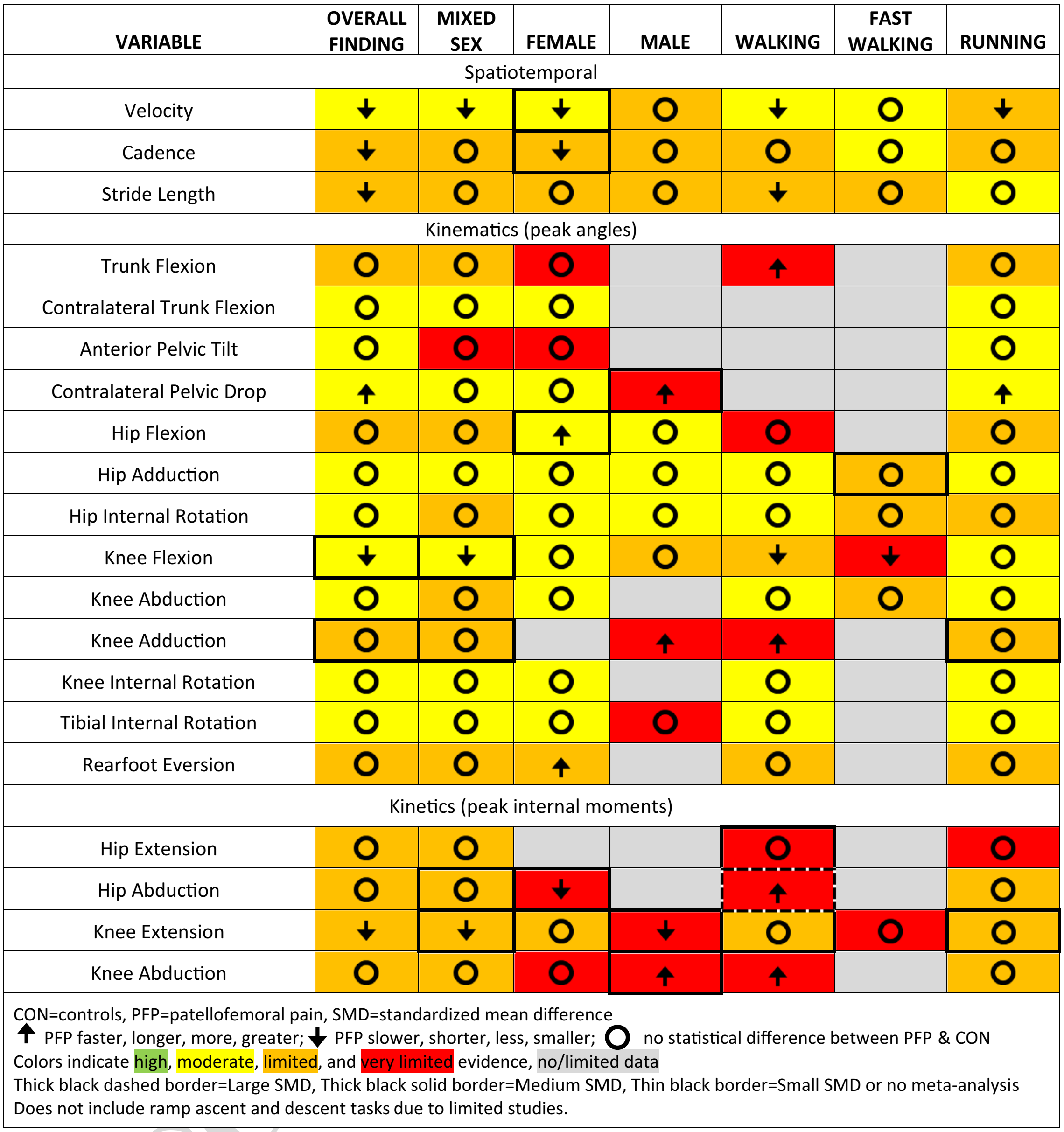

Fig. 2 Evidence Gap Map of gait biomechanics in people with and without petellofemoral pain

running (moderate evidence), or fast walking (limited evidence).

3.7.10 Knee Adduction Angle

Limited evidence indicates that peak knee adduction angles in people with PFP are not different to controls.

Sex: Peak knee adduction angles in mixed-sex groups and males with PFP are not different to controls and pain-free males (limited and very limited evidence, respectively).

Task: Peak knee adduction angle in people with PFP is not different to controls during running (limited evidence). Peak knee adduction angle in people with PFP is greater than controls during walking (very limited evidence).

3.7.11 Knee Internal Rotation Angle

Moderate evidence indicates that peak knee internal rotation angle in people with PFP is not different to controls.

Sex: Peak knee internal rotation angle in mixed-sex groups (moderate evidence) and females (moderate evidence) with PFP groups is not different to controls. No studies that were included in this meta-analysis included male groups and measured knee rotation angles.

Table 4 Spatiotemporal gait characteristics of people with and without patellofemoral pain across sex and task

Variable	Analysis	Studies and quality	Level of evidence	I^2	SMD (95% CI)	SMD size
Velocity	Overall	1 HQ [75] 16 MQ [17, 33, 34, 40, 43, 47, 49, 50, 55, 56, 59, 64, 70–73] 5 LQ [37, 44, 62, 67, 76]	Moderate	72%	– 0.50 (– 0.72, – 0.27)	Small*
	Mixed-sex	8 MQ [17, 34, 40, 43, 47, 49, 59, 73] 3 LQ [44, 62, 67]	Moderate	0%	– 0.20 (– 0.40, – 0.06)	Small*
	Females	1 HQ [75] 7 MQ [33, 55, 56, 64, 70–72] 2 LQ [37, 76]	Moderate	78%	– 0.64 (– 1.04, – 0.25)	Medium*
	Males	2 MQ [37, 50] 1 LQ [37]	Limited	88%	– 0.55 (– 1.52, 0.43)	Small
	Running	5 MQ [47, 49, 59, 64, 73] 2 LQ [37, 44]	Limited	59%	– 0.40 (– 0.74, – 0.06)	Small*
	Walking	1 HQ [75] 11 MQ [17, 33, 34, 40, 43, 50, 55, 56, 70–72] 4 LQ [37, 62, 67, 76]	Moderate	69%	– 0.38 (– 0.68, – 0.08)	Small*
	Fast walking	1 HQ [75] 3 MQ [17, 70, 71]	Moderate	64%	– 0.45 (– 1.07, 0.17)	Small
	Ramp ascent	1 MQ [70]	Very limited	–	–	–
	Ramp descent	1 MQ [70]	Very limited	–	–	–
Cadence	Prospective	1 HQ [58]	Limited	–	–	–
	Overall	9 MQ [17, 33, 47, 50, 53, 63, 70–72] 2 LQ [37, 62]	Limited	72%	– 0.43 (– 0.74, – 0.12)	Small*
	Mixed-sex	3 MQ [17, 47, 53] 1 LQ [62]	Moderate	0%	– 0.01 (– 0.38, 0.36)	Small
	Females	5 MQ [33, 63, 70–72] 1 LQ [37]	Limited	74%	– 0.75 (– 1.20, – 0.31)	Medium*
	Males	3 MQ [33, 50, 63] 1 LQ [37]	Limited	73%	– 0.12 (– 0.72, 0.47)	Small
	Running	2 MQ [47, 63] 1 LQ [37]	Limited	81%	– 0.43 (– 1.33, 0.48)	Small
	Walking	7 MQ [17, 33, 50, 53, 70–72] 2 LQ [37, 62]	Limited	67%	– 0.34 (– 0.72, 0.04)	Small
	Fast walking	3 MQ [17, 70, 71]	Moderate	41%	– 0.24 (– 0.82, 0.34)	Small
	Ramp ascent	1 MQ [70]	Very limited	–	–	–
	Ramp descent	1 MQ [70]	Very limited	–	–	–
Stride length	Overall	7 MQ [17, 33, 50, 51, 70–72] 2 LQ [37, 62]	Limited	72%	– 0.46 (– 0.80, – 0.12)	Small*
	Mixed-sex	1 MQ [17] 1 LQ [62]	Limited	54%	– 0.55 (– 1.43, 0.33)	Small
	Females	5 MQ [33, 51, 70–72] 1 LQ [37]	Limited	78%	– 0.46 (– 0.93, 0.02)	Small
	Males	2 MQ [33, 50] 1 LQ [37]	Limited	75%	– 0.44 (– 1.10, 0.32)	Small
	Running	1 MQ [51] 1 LQ [37]	Moderate	0%	– 0.30 (– 0.83, 0.23)	Small
	Walking	6 MQ [17, 33, 50, 70–72] 2 LQ [37, 62]	Limited	65%	– 0.44 (– 0.82, – 0.06)	Small*
	Fast walking	3 MQ [17, 70, 71]	Limited	91%	– 0.25 (– 1.86, 1.37)	Small
	Ramp ascent	1 MQ [70]	Very limited	–	–	–
	Ramp descent	1 MQ [70]	Very limited	–	–	––

CI confidence interval, *HQ* high-quality, *LQ* low-quality, *MQ* moderate-quality, *SMD* standardized mean difference

*Significant effect

Table 5 Trunk, pelvis, and lower extremity kinematics of people with and without patellofemoral pain across sex and task

Variable	Analysis	Studies and quality	Level of evidence	I^2 (%)	SMD (95% CI)	SMD size
Trunk flexion angle	Overall	4 MQ [36, 39, 43, 85]	Limited	78%	0.29 (– 0.39, 0.97)	Small
	Mixed-sex	3 MQ [36, 39, 43]	Limited	74%	0.53 (– 0.16, 1.22)	Small
	Females	1 MQ [85]	Very limited	–	–	–
	Running	3 MQ [36, 39, 85]	Limited	68%	0.03 (– 0.61, 0.67)	Small
	Walking	1 MQ [43]	Very limited	–	–	–
Contralateral trunk flexion angle	Overall	1 HQ [84] 3 MQ [36, 64, 85]	Moderate	0%	0.22 (– 0.14, 0.57)	Small
	Mixed-sex	1 HQ [84] 1 MQ [36]	Moderate	0%	0.10 (– 0.43, 0.64)	Small
	Females	2 MQ [64, 85]	Moderate	33%	0.31 (– 0.28, 0.91)	Small
	Running	1 HQ [84] 3 MQ [36, 64, 85]	Moderate	0%	0.22 (– 0.14, 0.57)	Small
Anterior pelvic tilt angle	Overall	2 MQ [36, 85]	Moderate	0%	– 0.41 (– 0.88, 0.06)	Small
	Mixed-sex	1 MQ [36]	Very limited	–	–	–
	Females	1 MQ [85]	Very limited	–	–	–
	Running	2 MQ [36, 85]	Moderate	0%	– 0.41 (– 0.88, 0.06)	Small
Contralateral pelvic drop angle	Overall	1 HQ [84] 6 MQ [36, 39, 47, 64, 82, 85]	Moderate	62%	– 0.46 (– 0.90, – 0.03)	Small*
	Mixed-sex	1 HQ [84] 2 MQ [36, 39]	Moderate	63%	– 0.58 (– 1.27, 0.10)	Small
	Females	3 MQ [47, 64, 85]	Moderate	42%	– 0.12 (– 0.65, 0.41)	Small
	Males	1 MQ [82]	Very limited	–	–	–
	Running	1 HQ [84] 6 MQ [36, 39, 47, 64, 82, 85]	Moderate	62%	– 0.46 (– 0.90, – 0.03)	Small*
Hip flexion angle	Overall	3 MQ [36, 49, 63] 1 LQ [37]	Limited	55%	0.12 (– 0.26, 0.50)	Small
	Mixed-sex	2 MQ [36, 49]	Limited	82%	– 0.20 (– 1.05, 0.64)	Small
	Females	1 MQ [63] 1 LQ [37]	Moderate	0%	0.83 (0.30, 1.36)	Medium*
	Males	1 MQ [63] 1 LQ [37]	Moderate	0%	– 0.24 – 0.75, 0.27)	Small
	Running	3 MQ [36, 49, 63] 1 LQ [37]	Limited	53%	0.07 (– 0.34, 0.48)	Small
	Walking	1 LQ [37]	Very limited	–	–	–

Table 5 (continued)

Variable	Analysis	Studies and quality	Level of evidence	I^2 (%)	SMD (95% CI)	SMD size
Hip adduction angle	Prospective	1 MQ [66]	Very limited	–	–	–
	Overall	2 HQ [75, 84] 11 MQ [35, 36, 38, 39, 47, 49, 63–65, 78, 82] 4 LQ [44, 67, 68, 80]	Moderate	63%	0.11 (– 0.13, 0.35)	Small
	Mixed-sex	1 HQ [84] 4 MQ [35, 36, 39, 49] 2 LQ [44, 67]	Moderate	73%	0.06 (– 0.35, 0.48)	Small
	Females	1 HQ [75] 6 MQ [38, 47, 63–65, 78] 2 LQ [68, 80]	Moderate	65%	0.13 (– 0.25, 0.50)	Small
	Males	2 MQ [63, 82] 1 LQ [68]	Moderate	17%	0.21 (– 0.35, 0.77)	Small
	Running	1 HQ [84] 10 MQ [36, 38, 39, 47, 49, 63–65, 78, 82] 2 LQ [47, 69, 80]	Moderate	65%	0.20 (– 0.07, 0.48)	Small
	Walking	1 HQ [75] 1 MQ [35] 1 LQ [67]	Moderate	0%	– 0.14 (– 0.53, 0.25)	Small
	Fast Walking	1 HQ [75]	Limited	–	–	–
Hip internal rotation angle	Prospective	1 MQ [66]	Very limited	–	–	–
	Overall	1 HQ [75] 12 MQ [34, 36, 38, 47, 49, 63–65, 77, 78, 82, 83] 4 LQ [44, 67, 68, 80]	Moderate	68%	0.08 (– 0.19, 0.34)	Small
	Mixed-sex	3 MQ [34, 36, 49] 2 LQ [44, 67]	Limited	58%	– 0.24 (– 0.64, 0.15)	Small
	Females	1 HQ [75] 8 MQ [38, 47, 63–65, 77, 78, 83] 2 LQ [68, 80]	Moderate	76%	0.20 (– 0.21, 0.62)	Small
	Males	2 MQ [63, 82] 1 LQ [68]	Moderate	0%	0.21 (– 0.26, 0.68)	Small
	Running	11 MQ [36, 38, 47, 49, 63–65, 77, 78, 82, 83] 3 LQ [44, 68, 80]	Limited	73%	0.32 (– 0.00, 0.64)	Small
	Walking	1 HQ [75] 1 MQ [35] 1 LQ [67]	Moderate	32%	– 0.38 (– 0.86, 0.11)	Small
	Fast Walking	1 HQ [75]	Limited	–	–	–

Table 5 (continued)

Variable	Analysis	Studies and quality	Level of evidence	I^2 (%)	SMD (95% CI)	SMD size
Knee flexion angle	Overall	1 HQ [84] 13 MQ [34, 36, 39, 40, 43, 50, 57, 63, 71, 81–83, 85] 4 LQ [37, 67, 68, 80]	Moderate	51%	– 0.30 (– 0.52, – 0.08)	Small*
	Mixed-sex	1 HQ [84] 6 MQ [34, 36, 39, 40, 43, 81] 2 LQ [67, 68]	Moderate	0%	– 0.41 (– 0.64, – 0.18)	Small*
	Females	5 MQ [57, 63, 71, 83, 85] 2 LQ [37, 80]	Moderate	31%	– 0.03 (– 0.34, 0.28)	Small
	Males	3 MQ [50, 63, 82] 1 LQ [37]	Limited	73%	– 0.59 (– 1.24, 0.06)	Small
	Running	1 HQ [84] 8 MQ [36, 39, 57, 63, 81–83, 85] 2 LQ [37, 68]	Moderate	40%	– 0.19 (– 0.46, 0.09)	Small
	Walking	5 MQ [34, 40, 43, 50, 71] 2 LQ [37, 67]	Limited	61%	– 0.32 (– 0.79, 0.15)	Small
	Fast walking	1 MQ [71]	Very limited	–	–	–
Knee abduction angle	Overall	1 HQ [75] 7 MQ [34, 36, 38, 57, 65, 73, 85] 1 LQ [48]	Moderate	34%	0.03 (– 0.23, 0.30)	Small
	Mixed-sex	3 MQ [34, 36, 73] 1 LQ [48]	Limited	61%	0.40 (– 0.15, 0.95)	Small
	Females	1 HQ [75] 4 MQ [38, 57, 65, 85]	Moderate	0%	– 0.18 (– 0.46, 0.09)	Small
	Running	6 MQ [36, 38, 57, 65, 73, 85] 1 LQ [48]	Moderate	49%	0.16 (– 0.21, 0.52)	Small
	Walking	1 HQ [75] 1 MQ [34]	Moderate	0%	– 0.22 (– 0.65, 0.21)	Small
	Fast Walking	1 HQ [21]	Limited	–	–	–
Knee adduction angle	Overall	1 MQ [82] 2 LQ [44, 67]	Limited	74%	0.83 (– 0.05, 1.70)	Medium
	Mixed-sex	2 LQ [44, 67]	Limited	76%	0.63 (– 0.61, 1.86)	Medium
	Males	1 MQ [82]	Very limited	–	–	–
	Running	1 MQ [82] 1 LQ [44]	Limited	83%	0.64 (– 0.51, 1.79)	Medium
	Walking	1 LQ [67]	Very limited	–	–	–
Knee internal rotation angle	Overall	7 MQ [34, 36, 38, 57, 65, 72, 85] 2 MQ [74, 80]	Moderate	0%	– 0.04 (– 0.26, 0.18)	Small
	Mixed-sex	2 MQ [34, 36] 1 LQ [74]	Moderate	0%	– 0.17 (– 0.53, 0.19)	Small
	Females	5 MQ [38, 57, 65, 72, 85] 1 LQ [80]	Moderate	1%	– 0.04 (– 0.03, 0.21)	Small
	Running	5 MQ [36, 38, 57, 65, 85] 2 LQ [74, 80]	Moderate	0%	0.04 (– 0.25, 0.32)	Small
	Walking	2 MQ [34, 72]	Moderate	0%	– 0.02 (– 0.45, 0.40)	Small

Table 5 (continued)

Variable	Analysis	Studies and quality	Level of evidence	I^2 (%)	SMD (95% CI)	SMD size
Tibial internal rotation angle	Overall	6 MQ [35, 56, 59, 64, 72, 82] 1 LQ [74]	Moderate	0%	0.20 (− 0.04, 0.44)	Small
	Mixed-sex	2 MQ [35, 59] 1 LQ [74]	Moderate	0%	0.14 (− 0.20, 0.48)	Small
	Females	3 MQ [56, 64, 72]	Moderate	2%	0.35 (− 0.05, 0.76)	Small
	Males	1 MQ [82]	Very limited	–	–	–
	Running	3 MQ [59, 64, 82] 1 LQ [74]	Moderate	28%	0.17 (− 0.20, 0.55)	Small
	Walking	3 MQ [35, 56, 72]	Moderate	0%	0.25 (− 0.12, 0.62)	Small
Rearfoot eversion angl	Prospective	1 MQ [22]	Very limited	–	–	–
	Overall	8 MQ [34, 41, 46, 55, 56, 59, 61] 1 LQ [60]	Limited	85%	0.10 (− 0.41, 0.60)	Small
	Mixed-sex	2 MQ [34, 46, 59, 61] 1 LQ [60]	Limited	90%	− 0.24 (− 0.98, 0.50)	Small
	Females	4 MQ [41, 55, 56, 65]	Limited	52%	0.59 (0.03, 1.14)	Small*
	Running	4 MQ [46, 59, 61, 65] 1 LQ [60]	Limited	90%	− 0.20 (− 0.96, 0.56)	Small
	Walking	4 MQ [34, 41, 55, 56]	Limited	61%	0.50 (− 0.08, 1.09)	Small

CI confidence interval, *HQ* high-quality, *LQ* low-quality, *MQ* moderate-quality, *SMD* standardized mean difference

*Significant effect

Task: Peak knee internal rotation angle in PFP is not different to controls during walking (moderate evidence) and running (moderate evidence).

3.7.12 Tibial Internal Rotation Angle

Moderate evidence indicates that peak tibial internal rotation angle in people with PFP is not different to controls.

Sex: Peak tibial internal rotation angle in mixed-sex groups (moderate evidence), females (moderate evidence), and males (very limited evidence) with PFP is not different to controls.

Task: Peak tibial internal rotation angle in PFP is not different to controls during running (moderate evidence) and walking (moderate evidence).

3.7.13 Rearfoot Eversion Angle

Very limited evidence indicates no prospective association between peak rearfoot eversion angle and runners who subsequently develop PFP.

Limited evidence indicates that peak rearfoot eversion angle in people with PFP is not different to controls.

Sex: Peak rearfoot eversion angle for mixed-sex groups with PFP is not different to controls (limited evidence). Peak rearfoot eversion angle in females with PFP is greater compared to pain-free females (limited evidence; $I^2 = 52\%$, small significant SMD 0.59, 95% CI 0.03, 1.14). There were no studies found that reported peak rearfoot eversion angle during walking or running in males alone.

Task: Peak rearfoot eversion angle in people with PFP is not different to controls during running (limited evidence) or walking (limited evidence).

3.8 Joint Kinetics

A limited number of studies were found that reported data on joint kinetics in people with PFP and pain-free controls, including data for the hip [36, 38, 67] and knee [17, 36–38, 40, 43, 67, 79–83]. All moments were reported as internal moments except one study that reported external moments [82] and one study that did not report moment type [40]. Only significant differences derived through meta-analysis are accompanied by supporting statistics. A summary of kinetic results is provided below, and in the evidence gap map (Fig. 2). Complete results from meta-analyses can be seen in Table 6 and forest plots are provided in Online Resource 7 (OSM).

3.8.1 Hip Extension Moment

Limited evidence indicates that peak hip extension moment is not different in people with PFP compared with controls.

Table 6 Trunk, pelvis, and lower extremity kinematics of people with and without patellofemoral pain across sex and task

Variable	Analysis	Studies and quality	Level of evidence	I^2	SMD (95% CI)	SMD size
Hip extension moment	Overall	1 MQ [36] 1 LQ [67]	Limited	74%	− 0.03 (− 1.16, 1.10)	Small
	Mixed-sex	1 MQ [36] 1 LQ [67]	Limited	74%	− 0.03 (− 1.16, 1.10)	Small
	Running	1 MQ [36]	Very limited	–	–	–
	Walking	1 LQ [67]	Very limited	–	–	–
Hip abduction moment	Overall	2 MQ [36, 38] 1 LQ [67]	Limited	87%	0.44 (− 0.77, 1.65)	Small
	Mixed-sex	1 MQ [36] 1 LQ [67]	Limited	76%	1.02 (− 0.30, 2.34)	Medium
	Females	1 MQ [38]	Very limited	–	–	–
	Running	2 MQ [36, 38]	Limited	82%	− 0.12 (− 1.18, 0.95)	Small
	Walking	1 LQ [67]	Very limited	–	–	–
Knee extension moment	Overall	6 MQ [17, 36, 40, 43, 81, 83] 3 LQ [37, 67, 80]	Limited	56%	− 0.44 (− 0.76, − 0.09)	Small*
	Mixed-sex	5 MQ [17, 36, 40, 43, 81] 1 LQ [68]	Limited	63%	− 0.67 (− 1.17, − 0.16)	Medium*
	Females	1 MQ [83] 2 LQ [37, 80]	Moderate	16%	0.05 (− 0.35, 0.44)	Small
	Males	1 LQ [37]	Very limited	–	–	–
	Running	3 MQ [36, 81, 83] 2 LQ [37, 80]	Moderate	39%	− 0.20 (− 0.59, 0.18)	Small
	Walking	3 MQ [17, 40, 43] 2 LQ [37, 67]	Limited	68%	− 0.67 (− 1.28, − 0.05)	Medium*
	Fast walking	1 MQ [17]	Very limited	–	–	–
Knee abduction moment	Overall	3 MQ [36, 38, 82] 1 LQ [68]	Limited	68%	0.26 (− 0.38, 0.90)	Small
	Mixed-sex	1 MQ [36] 1 LQ [67]	Limited	81%	0.39 (− 0.98, 1.76)	Small
	Females	1 MQ [38]	Very limited	–	–	–
	Males	1 MQ [82]	Very limited	–	–	–
	Running	3 MQ [36, 38, 82]	Limited	62%	0.05 (− 0.56, 0.65)	Small
	Walking	1 LQ [67]	Very limited	–	–	–

CI confidence interval, *HQ* high-quality, *LQ* low-quality, *MQ* moderate-quality, *SMD* standardized mean difference

*Significant effect

Task: Peak hip extension moment in PFP is not different to controls during running (very limited evidence) or walking (very limited evidence).

3.8.2 Hip Abduction Moment

Limited evidence indicates that peak hip abduction moment in PFP is not different to controls.

Sex: Peak hip abduction moment in mixed-sex PFP groups is not different to controls (limited evidence). Peak hip abduction moment in females with PFP is lower compared with pain-free females (very limited evidence).

Task: Peak hip abduction moment in PFP is not different to controls during running (limited evidence), and higher during walking (very limited evidence).

3.8.3 Knee Extension Moment

Limited evidence indicates that the peak knee extension moment in people with PFP is smaller compared with controls ($I^2 = 56\%$, small significant SMD − 0.43, 95% CI − 0.76, − 0.09).

Sex: Peak knee extension moment in mixed-sex PFP groups is smaller compared with controls (limited evidence; $I^2 = 63\%$, medium significant SMD − 0.67, 95% CI − 1.17, − 0.16). Knee extension moment in females (moderate evidence) and males (very limited evidence) with PFP is not different to controls.

Task: Peak knee extension moment in PFP is not different to controls during running (moderate evidence) and fast walking (very limited evidence). Peak knee extension moment in people with PFP is smaller compared to controls during walking (limited evidence; $I^2 = 68\%$, medium significant SMD − 0.67, 95% CI − 1.28, − 0.05).

3.8.4 Knee Abduction Moment

Limited evidence indicates that peak knee abduction moment in people with PFP is not different to controls.

Sex: Peak knee abduction moment in mixed-sex groups (limited evidence) and females (very limited evidence) with PFP is not different to controls. Peak knee abduction moment is greater in males with PFP compared with pain-free males (very limited evidence).

Task: Peak knee abduction moment in PFP is not different to controls during running (limited evidence) and is greater during walking (very limited evidence).

3.8.5 Knee External Rotation Moments

In mixed-sex groups, peak knee external rotation moment in PFP is greater compared with controls during walking (very limited evidence) but not different during running (very limited evidence).

4 Discussion

After synthesizing all biomechanics data during walking and running, we identified some differences between people with and without PFP. People with PFP ambulate with lower gait velocity, stride length, and cadence, lower knee flexion angles and knee extension moments, and greater contralateral pelvic drop compared with pain-free controls. Additionally, females (but not males) with PFP ambulate with greater hip flexion and rearfoot eversion; and greater contralateral pelvic drop occurs during running (but not walking) in people with PFP. Large inter-study variability in biomechanical methodology and reporting, and low-to-moderate study quality, means that these findings should be interpreted with caution.

4.1 Spatiotemporal Gait Characteristics

Reduced gait velocity, cadence, and stride length identified in people with PFP is consistent with findings in people with knee [87] and patellofemoral [88] osteoarthritis, and have been reported to be associated with worsening structural disease [88]. No prospective associations between spatiotemporal variables and PFP development were identified; only running cadence has been prospectively investigated and was not different in those who developed PFP [58]. These spatiotemporal gait characteristics can be monitored in clinic, and increasing cadence can reduce knee joint loads during walking [89] and running [81], making them potential therapeutic targets.

4.2 Kinematics

No prospective studies evaluating knee flexion kinematics were identified, despite prospective evidence that decreased knee extensor strength is a risk factor for PFP in military populations [4], representing an important knowledge gap. However, our findings did indicate that peak knee flexion during walking is lower in people with PFP compared with pain-free controls. Smaller knee flexion angles, and the resulting reduced patellofemoral joint reaction forces, may reflect a compensatory strategy used by people with PFP to control pain [16, 19]. The avoidance of painful movement may be related to kinesiophobia (i.e., fear of movement) and/or crepitus, both of which have been reported to be associated with reduced knee flexion angles during stair ascent in females with PFP [20, 90]. Clinicians could consider restoring appropriate knee flexion in people with PFP with strategies to reduce pain, kinesiophobia, or crepitus-related fear.

We did not identify higher knee abduction angles in people with PFP during walking or running, with none of the included studies reporting significant differences [34, 36, 38, 48, 57, 64, 73, 75, 85]. Increased frontal plane motion of the knee (i.e., abduction or valgus) has been proposed to contribute to PFP by increasing lateral PFJ reaction force [16, 91, 92] and elevated PFJ stress [16]. There is also moderate evidence from Neal et al. [4] that frontal plane knee motion is not associated with the development of PFP. While knee abduction can be observed clinically as part of dynamic knee valgus, hip adduction contributes to this observation [93, 94], and clinicians should be cautious when making associations between frontal plane knee motion and the development and persistence of PFP.

Our meta-analysis indicates that people with PFP do not ambulate with greater hip adduction or internal rotation during walking, fast walking, or running when compared with pain-free controls. This finding was surprising given the common proposal that increased hip adduction and internal rotation lead to altered tibiofemoral kinematics and increased patellofemoral joint loading [16]. Previous systematic reviews have reported increased hip adduction and internal rotation in people with PFP [22, 95], but these reviews either limited their analysis to running only [22] or included a variety of tasks in addition to gait [95]. These conflicting results could also be influenced by measurement error of transverse plane motion [96] and the additional studies included in our updated review. Despite the absence of a difference between people with and without PFP, it is still plausible that the magnitude of hip adduction during running may contribute to the onset and/or persistence of PFP. Our review did identify very limited evidence that greater hip adduction, but not internal rotation, during running is prospectively associated with the future development of PFP in female runners [66]. Variability in hip adduction and internal rotation results could reflect compensatory strategies in people with PFP to reduce pain [16, 34, 72], but kinematics are not reported to be impacted by acute changes in knee pain [97]. Assessment of hip kinematics in runners with PFP may also inform running retraining strategies. For female runners with PFP who demonstrate hip adduction greater than 20°, 2 weeks of running retraining to reduce hip adduction provided a significant reduction in pain for up to 3 months [98, 99]. Our review indicates that frontal and transverse plane motion of the hip are not consistently biomechanical factors of relevance for all people with PFP but should be further evaluated with consistent high-quality methodologies and prospective designs.

We identified no differences in trunk motion in people with PFP compared with pain-free controls, but did identify greater contralateral pelvic drop during running. This is consistent with the findings of Neal et al. [22] with the addition of one MQ study. A level pelvis is proposed to maintain alignment between the body's centre of mass and the knee joint, reducing frontal plane moments at the knee [100]. Pelvic shift may also be a compensation strategy for hip abductor weakness [15] and/or lack of pelvic control [100]. Aligning with our findings, a 1° increase in contralateral pelvic drop during running has been reported to be associated with an 80% increased odds of being classified as an injured runner, although this is not specific to PFP [39]. Including frontal plane pelvis kinematics in research and clinical gait analysis will facilitate better understanding of the role of the pelvis in PFP.

We identified greater rearfoot eversion in females with PFP, but not in mixed-sex cohorts. A single study [55] seems to have driven these results, with the SMD for this study (SMD = 1.55) three times greater than the next largest SMD (0.52) [41]. We identified no difference in rearfoot eversion in combined sex groups or during specific tasks, and no data have been reported in male-only cohorts. Our findings are consistent with Selfe et al. [101], who reported that a subgroup of people with PFP exists where rearfoot posture is important and this subgroup was composed primarily of females. Prefabricated foot orthoses demonstrate short-term efficacy in people with PFP [102, 103], especially those with greater rearfoot eversion [104], although it is unclear whether therapeutic effects are related to small changes in biomechanics observed with foot orthoses (primarily at the ankle) [105]. Further studies are needed to clarify the relationship between rearfoot kinematics and the development and treatment of PFP.

4.3 Kinetics

Pooled data from nine studies indicates that internal knee extension moments are smaller in people with PFP. Lower knee extensor moments could reflect a compensatory strategy to reduce pain, or avoidant behaviour. Lower internal knee extension moments can result in lower PFJ reaction force [16]; however, PFJ reaction forces and pressure during stair descent are not related to self-reported pain or disability in women with PFP [20]. As lower knee extensor strength has been reported as a risk factor for the development of PFP [4], prospective studies are necessary to understand the role of knee joint kinetics in PFP.

This is the first systematic review to summarize the evidence for altered lower extremity joint moments in people with PFP [16]. We identified no differences when pooling hip joint kinetics from three studies [36, 38, 67] in people with PFP compared with pain-free controls. Hip extension and abduction moments are influenced by sagittal plane trunk and frontal plane trunk and pelvis motion, respectively [106], and we identified that people with PFP demonstrate greater frontal plane pelvis motion compared to controls. Hip joint moments may also be sensitive to acute increases in pain, with reduced hip joint moments reported following both experimentally induced knee pain in pain-free people [107] and functionally increased pain in people with PFP [97]. More research is required to understand the role of hip joint kinetics in the development, persistence, and treatment of PFP.

4.4 Biomechanics Quality of Reporting Assessment

Commonly reported biomechanical items were the data collection equipment (98%), sampling rate (89%), and adequately defined variables of interest (87%). Consistently unreported biomechanical items were those describing the biomechanical model, including defined joint centres (24%), coordinate system descriptions (35%), and segment descriptions (42%). Despite the ISB recommendations [29, 30] specifically indicating that the coordinate systems should be defined, this information was often absent. Author omission or requests from editors to remove technical information to improve concision may explain these unreported items. A very small number of studies (17%) reported lab-specific reliability measures, which should be published, including standard error of measure and minimal detectable change values, to allow differentiation between statistically and "clinically" significant differences. Emerging evidence indicates that biomechanical variables may be accurately and reliably collected across multiple labs and over longer periods of time [108, 109]. Reporting greater methodological details of biomechanics studies will facilitate study replication and reduce heterogeneity for future meta-analyses.

Although our proposed ‘Biomechanics Reporting Checklist’ was found to have excellent inter-rater agreement (92% agreement in this review (range: 78–100%)), it has not been validated. A Delphi approach to further refine and validate this checklist is warranted.

4.5 Limitations and Future Research

Our results should be considered in the context of their limitations. Prospective data are needed to adequately address the question of whether biomechanical variables are associated with PFP development. We were only able to include three prospective studies compared to 52 case–control studies. We included studies involving walking, ramp walking, and running. Other tasks that require substantial knee flexion (e.g., squatting, jumping, stair ambulation) may provide differing results. Most included studies were assessed to be of MQ based on the modified NOS, limiting the strength of the eventual evidence. Future studies are advised to focus carefully on methodological quality to ensure positive contribution to the existing literature. The NOS has been suggested to be more appropriate as a quality of reporting scale. However, it has also been recommended as a risk of bias tool [110]. The approach of organizing studies into quality categories is limited because the categories are arbitrarily chosen, but are required to apply the van Tulder criteria [32]. Studies commonly reported a clear definition of PFP, though this definition was often poorly aligned with the consensus definition [1], which may result in people with diagnoses other than PFP being inappropriately included in this review. The Biomechanics Reporting Checklist is also limited in that it has not undergone a comprehensive process of development and testing, and it was reviewed by small number of experts selected by the authors. Consultation with a different set of reviewers may have resulted in different checklist content. This review only included studies published in the English language and publication bias was not assessed.

While the number of studies evaluating biomechanics in people with PFP has increased substantially since Barton et al. [21], the clarity of the findings has not increased with the same magnitude, likely due to studies with small sample sizes, high risk of bias, and a lack of prospective data. This means that the clinical implications of biomechanical studies in PFP still require further research to clearly identify and delineate. Accounting for differences in spatiotemporal gait characteristics through appropriate methodological or statistical approaches should also be considered in all biomechanical studies of PFP to ensure valid results. Biomechanical differences between people with and without PFP may be more clearly identified during tasks other than gait, and very few studies have reported biomechanics during multiple tasks together [2]. Future biomechanical studies should also consider publishing results for males and females separately and include this consideration in a priori power analyses.

5 Conclusion

The evidence for biomechanical characteristics of walking and running and their association with PFP is limited by low-to-moderate levels of evidence. Our findings indicate that, compared with pain-free controls, people with PFP ambulate slower, with lower cadence, and a shortened stride length, greater contralateral pelvic drop, and lower knee flexion angles and knee extension moments. Greater hip flexion and rearfoot eversion angles were evident in females, but data to make conclusions about males were very limited.

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