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Review

Methods to assess patellofemoral joint stress: A systematic review

Guilherme S. Nunes[a,*], Rodrigo Scattone Silva[b], Ana Flávia dos Santos[a], Ricardo A.S. Fernandes[c], Fábio Viadanna Serrão[a], Marcos de Noronha[d]

[a] Department of Physiotherapy, Federal University of São Carlos, São Carlos, Brazil
[b] Faculty of Health Sciences of Trairi, Federal University of Rio Grande do Norte, Santa Cruz, Brazil
[c] Department of Electrical Engineering, Federal University of São Carlos, São Carlos, Brazil
[d] Department of Community and Allied Health, La Trobe University, Bendigo, VIC, Australia

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ABSTRACT

Changes in patellofemoral joint (PFJ) stress are related to the development and course of PFJ dysfunctions. Different methods for PFJ stress calculation have been used, making the comparison of PFJ stress values across different studies difficult. The purpose of this study was to systematically review the methods for PFJ stress calculation and highlight the differences among the methods. A systematic literature search was conducted in Medline, Embase, CINAHL, SPORTDiscus and Web of Science databases. Included studies examined PFJ stress in subjects with or without musculoskeletal conditions. Of 12,670 identified studies, 53 were included, with a total of 1134 subjects evaluated. The main differences among the methods to calculate PFJ stress were: i) method to calculate PFJ contact area; ii) method to calculate a constant (coefficient k) that defines the relation between quadriceps force and PFJ reaction force; iii) the inclusion of adjustments for sagittal plane forces. Considerable variability in PFJ stress results was observed. The greatest PFJ stress value was 55.03 MPa during a dance jump and the lowest value was 1.9 MPa during walking at the speed of 1.4 m/s. Most studies applied methods which use data from previous studies. However, methods which use data from their own participants for most parts of the calculation might be preferred to minimize potential errors. When direct measures are not possible, a standard method could be applied to facilitate comparisons among studies.

1. Introduction

Patellar malalignment is a common finding in people with patellofemoral joint (PFJ) pain [1] and PFJ osteoarthritis [2], the two main PFJ dysfunctions. The association between patellar malalignment and the resultant force from quadriceps muscle and patellar tendon actions [3] may contribute to the progression of PFJ dysfunctions. Due to changes on PFJ contact area from the malalignment, PFJ reaction force may not be dissipated adequately [4]. Consequently, interferences on the relationship between patellar forces and patellar alignment may be related to pain and morphological changes such as osteophytes and loss of cartilage [2,5].

The relationship between patellar forces and contact area has been commonly investigated by measuring the stress these forces can create in the PFJ [6–10]. For PFJ stress calculations, the force imposed in the patella is divided by the contact area between the patella and femur [6,8,11,12]. PFJ stress measure has been reported during different activities such as running [13,14] and squatting [15,16]; also in different populations, such as those with PFJ pain [6] and those with PFJ osteoarthritis [17].

As PFJ stress cannot be directly measured *in vivo*, studies present data on PFJ stress based on mathematical models currently available in the literature [6,18,19]. The majority of the studies underwent the steps below described and presented in Fig. 1 in order to calculate PFJ stress:

1st step: kinematic and kinetic data are obtained from participants during some activity, usually with the use of cameras and force platforms. The knee flexion angle and knee extensor moment are measured and used in the PFJ stress mathematical model. Knee angles and moments are calculated indirectly through biomechanical models [20]. Although these measurements are considered reliable, there is the potential of miscalculating them [20]. In the sagittal plane knee angle calculations could have approximately five degrees of error during gait measurement [21] and knee extensor moment could have approximately 10 Nm of error during vertical drop jumps [22].

2nd step: quadriceps muscle effective lever arm (L_{eff}) is calculated. This is a step to estimate quadriceps force. Studies commonly use data previously published to develop a formula in which knee flexion angle is the dependent variable [6,18]. Data for the development of the formulas is based on measures from images of the knee in the sagittal

* Corresponding author: Rod. Washington Luis, km 235, Sã˚Carlos, SP, CEP 13565-905, Brazil.
E-mail address: nunesguilherme@live.com (G.S. Nunes).

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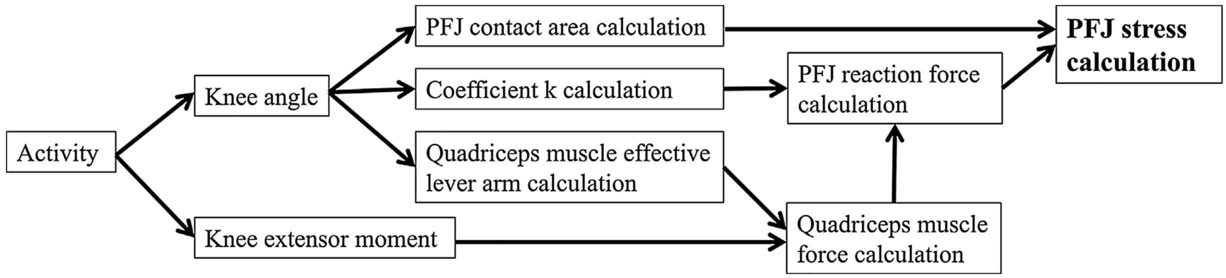

Fig. 1. Flow chart of PFJ stress calculation.

plane, from radiography or magnetic resonance imaging (MRI), and its accuracy is uncertain [9,23].

3rd step: quadriceps muscle force is calculated. This is a step to obtain PFJ reaction force. Knee extensor moment obtained during an activity is divided by the calculated L_{eff}. This step is required to isolate the force generated by the quadriceps muscle [24].

4th step: coefficient k is calculated. This is also a step for the PFJ reaction force calculation. Coefficient k is a constant that defines the relation between quadriceps force and PFJ reaction force as a function of knee flexion angle [9]. Studies usually use data previously published to develop a formula in which knee flexion angle is the dependent variable [25,26]. However it is difficult to know whether the theoretical approach used in some of the studies are likely to generate significant error in the estimates [9].

5th step: PFJ reaction force is calculated. The calculated quadriceps muscle force is multiplied by the calculated coefficient k. The estimated error in this measure is approximately 50N [27].

6th step: calculation of PFJ contact area. Most studies used previously published data to develop a formula in which knee flexion angle is the dependent variable [18,28]. Methods were developed based on the contact area of the PFJ of cadavers, healthy people and people with knee injuries [29,30]. The estimated error for PFJ contact area, measured by MRI, is approximately 40 mm^2 [31].

7th step: final step where PFJ stress is calculated by dividing PFJ reaction force by PFJ contact area.

Interestingly, although the majority of studies have reported to follow these steps, there are different mathematical models to reach values of PFJ stress. Some studies used a wider range of data from their participants as opposed to using data from previous studies as described above. These studies collected data via MRI and used the new collected data from their own participants to calculate PFJ contact area, L_{eff} and coefficient k [19,23]. The assumption of cocontraction of knee flexors and extensors is another difference among mathematical models to calculate PFJ stress [32,33].

Given the complexity of the methods and potential error associated to each method, it is difficult to compare results from studies that used different methods. This was demonstrated in the study by Kernozek et al. [16], where two methods to estimate quadriceps muscle force were compared and results showed a significant difference in PFJ stress of approximately 7 MPa [16]. For that reason, slight differences in the used methods for PFJ stress calculation could potentially lead to misinterpretation of the findings. Studies that used PFJ stress calculation might have been performed without the required attention which compromises the findings and potentially misleads readers who are interested in the PFJ stress field. It also highlights the importance of using consistent methods to calculate PFJ stress. Furthermore, some statements and hypotheses on PFJ dysfunctions, based on PFJ stress, indicate that some clinicians and researchers may be unfamiliar with the available methods used to calculate PFJ stress. For example, some studies suggest that the presence of excessive dynamic knee valgus during activities could increase the PFJ stress [34,35]. This statement may be true; however, no factor related to frontal plane is applied in the methods to calculate PFJ stress and therefore such statement is in disagreement with the present literature. Therefore, the aim of the current study was to systematically review the mathematical methods used in the literature to calculate PFJ stress and to potentially identify the best method to calculate PFJ stress. We also aimed at addressing the complexity of the methods by highlighting the differences among the methods.

2. Methods

This systematic review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement recommendations [36].

2.1. Eligibility criteria

To be included in this systematic review, the studies had to present PFJ stress measurements, with the evaluated participants being healthy or presenting any injury (e.g. PFJ pain, osteoarthritis). Studies with subjects submitted to surgical procedures were also included. Studies in which PFJ stress evaluations were conducted in cadavers or with animal models; in which joint stress was evaluated by means of computer simulation; and/or were published in languages other than English were excluded from the review. No restriction to study design was adopted.

2.2. Search strategy

The electronic search was conducted in the following databases: Medline and Embase via OVID, CINAHL and SPORTDiscus via EBSCO and Web of Science, from inception until September 2017. The search strategy used for Medline is presented in Supplementary material 1 (Table), with the terms adapted accordingly to the other databases.

2.3. Selections of the studies

The selection of the studies was conducted by two independent reviewers, first by titles, then by abstracts. In cases where there was no consensus between the reviewers, a third reviewer was consulted about the study's eligibility. Only the studies that potentially met the inclusion criteria had its full version analyzed. The reference lists were examined and the studies citing the included studies were also checked using Google Scholar (Supplementary material 2 – Flow diagram). A few conference abstracts and doctoral theses that met the study's objectives were also found in the databases. However, the methods and results of these were clearly related to published papers of the same authors. Thus, only the results of full-text published papers were considered for further analysis.

2.4. Evaluation of the methodological quality

In order to evaluate the quality of the studies, the Epidemiological Appraisal Instrument (EAI) was used [37]. For that we followed previous systematic reviews, we selected the relevant questions from the

Table 1
Used formulas and respective studies that cited the formula for quadriceps muscle effective lever arm calculation.

Formula used in the included studies	*Study reference number*
Measure directly from their sample using MRI	[23]
$L_{eff} = 8.0E-05 \times^{3} - 0.013 \times^{2} + 0.28\times + 0.046$	[6,12,13,18,25,26,40–42,45,46,48–50,52–59,61,62,64,66,68–70,72,75]
$L_{eff} = 8(10-8)(x^{\circ})3 + - 1.29(10-5)(x^{\circ})2 + 2.8(10-4)(x^{\circ}) + 0.0462$	[19]
For each quadriceps components (x = knee flexion angle in radians): ● RF = 0.0519235 − 0.0064865x ● VMO = $0.0021733 \times^{3} + 0.0089959 \times^{2} + 0.0059805x + 0.0434523$ ● VI = $0.0022705 \times^{3} + 0.0097213 \times^{2} + 0.0066606x + 0.044273$ ● VL = $0.0033264 \times^{3} + 0.0145048 \times^{2} + 0.0138364x + 0.0401728$	[16]
Formula is not presented; the only information given is that L_{eff} was based on data from previous study.	[7,8,15,17,28,32,33,43,44,47,51,60,67,71]

MRI: Magnetic resonance imaging; L_{eff}: Quadriceps muscle effective lever arm; x = knee flexion angle; RF: Rectus femoris; VMO: Vastus medialis obliquuos; VI: Vastus intermedius; VL: Vastus lateralis.

EAI and adapted according to the objectives of the present review [38,39]. Twenty four questions, from the original 46, were selected. Items related to interventions, randomization, follow-up and follow-up losses were excluded by consensus of the three reviewers. Each item was scored as: "Yes" (score 2), "Partial" (score 1), "No" (score 0), "Unable to determine" (score 0), or "Not Applicable" (item removed from the final score). The average of the scored items of each study was calculated with the final score ranging from 0 to 2. The studies were considered to be of high methodological quality when the average was higher than 1. Studies with an average score less than or equal to 1 were considered to have low methodological quality [38,39]. The quality of the included studies was assessed by two independent reviewers and, in cases of disagreement, a third reviewer was consulted. Title, journal and details about the authors were removed prior to the quality assessments.

2.5. Data extraction and analysis

Data extraction was completed independently by two reviewers. Data on the characterization of the included studies, PFJ stress values, mathematical models and variables used to calculate the PFJ stress were extracted. Studies included in this review were analyzed qualitatively.

3. Results

3.1. Study selection

A total of 12,670 titles were retrieved from the searches. In the initial search in five databases, a total of 9667 titles were found, of which 42 papers met the eligibility criteria (Supplementary material 2 – Flow diagram). After inclusion of the references of included papers and citation checking 3003 titles were further screened and 11 more papers met the eligibility criteria. These studies were not part of the databases searched in the current study or were *in press*.

Of the 53 included studies, 1134 subjects were evaluated regarding PFJ stress. Participants of the included studies were healthy subjects and patients with conditions such as PFJ pain, PFJ osteoarthritis, after Achilles tendon rupture, or submitted to knee arthroplasty and anterior cruciate ligament reconstruction, of both genders with age between 16 and 72 years. PFJ stress was evaluated during several activities which were classified into four categories for data presentation: running, walking, weight-bearing activities and jumping. The characteristics of the included studies are presented on Supplementary material 3 (Table). Regarding the methodological quality of the included studies, 36% presented high quality (n = 19) and 64% presented low quality (n = 34) (Supplementary material 4 – Table).

3.2. PFJ stress calculation

The variables used by the included studies in order to calculate PFJ stress were: knee flexion angle, quadriceps force (derived from knee extensor moment, quadriceps effective lever arm, quadriceps lever arm and its parts [rectus femoris, vastus medialis, vastus lateralis, and vastus intermedius], and patellar ligament lever arm), hamstring force (derived from hip extensor moment, hamstring lever arm, gluteus maximus lever arm, hamstring cross-sectional area, gluteus maximus cross-sectional area, lower limb kinematics, and hamstrings electromyography), gastrocnemius force (derived from ankle plantar flexion moment, triceps surae lever arm, gastrocnemius cross-sectional area, triceps surae cross-sectional area, lower limb kinematics, and gastrocnemius electromyography), relation between PFJ reaction force and quadriceps force (coefficient *k*), and PFJ contact area.

The majority of the included studies underwent the following steps in order to calculate PFJ stress: quadriceps muscle lever arm calculation, quadriceps muscle force calculation, PFJ reaction force calculation, ratio between quadriceps force and PFJ reaction force, PFJ contact area calculation and PFJ stress calculation. A detailed description of the methods of the included studies for calculating PFJ stress is presented on Supplementary material 5 (Table).

3.2.1. Quadriceps muscle effective lever arm

One study conducted direct measurements of the quadriceps muscle L_{eff} from the evaluated participants [23]. The remaining studies used previously published quadriceps muscle L_{eff} data to estimate quadriceps force (Table 1). Whyte et al. [19] presented a different formula compared to other studies. We unsuccessfully tried to contact the authors to understand the difference in formulas presented. Five studies did not mention any L_{eff} measurement [14,63,65,73,74].

Eight papers [9,10,76–81] were used as source for the L_{eff} calculation or formula development for such; however, most studies (33 studies [13,17,18,25,26,32,33,40–42,45,46,48,49,51–62,64,66–70,75]), direct or indirectly, used the data from van Eijden et al. [9].

3.2.2. Quadriceps muscle force

All included studies mentioned the quadriceps force calculation used in their study, except the studies by Hofmann et al. [73], Carpenter et al. [65] and Peng et al. [74]. Although Carpenter et al. [65] did not specifically mention quadriceps force, they used the compressive force applied to the plantar surface of the feet (simulation of weight-bearing inside a MRI machine) for the calculations of PFJ reaction force. Hofmann et al. [73] and Peng et al. [74] did not mention the method used for force calculation. Essentially, in order to obtain quadriceps force, most studies divided the knee extensor moment (obtained during the specific activities) by the previously calculated lever arm [6,8,12,13,16–19,23,25,26,32,33,40–43,45–62,64,66–70,72,75].

Seven studies adjusted the knee extensor moment by the knee flexor force, accounting for muscle co-contraction during the evaluated activities [32,33,43,44,47,51,67]. For these adjustments, Willy et al. [43], Willy et al. [47], Willson et al. [33] and Wilson et al. [44] used previously published data to calculate hamstrings and gastrocnemius forces. In order to estimate hamstring force, Willy et al. [47] and Willson et al. [33] used the cross-sectional area of the hamstring and gluteus maximus, with their respective lever arms in the hip joint, and also considered hip angle. For gastrocnemius force estimation, the triceps surae force was calculated using the plantar flexor moment and the lever arm of the Achilles tendon; then, the gastrocnemius force was calculated in proportion to the physiological cross-sectional area of the muscle. Teng and Powers [51], Chinkulprasert et al. [67] and Powers et al. [32] used kinematic data, muscle contraction velocity and electromyography data of the knee flexor muscles from their participants to estimate knee flexor muscle force. The studies that measured the knee flexor force [32,33,47,51,67] added this result to the knee extensor moment in order to obtain an adjusted knee extensor moment.

Simpson et al. [7] mentioned knee flexor muscle forces were calculated, however the authors did not clearly specify how the adjustments were made. The authors only mentioned that, for the quadriceps force calculations, previous data were interpolated as a function of the knee flexion angle [7].

Vannatta and Kernozek [14] and Kernozek et al. [63] estimated the quadriceps force using the Human Body Model, which includes kinematic and kinetic data in the calculations. Kernozek et al. [16] used two methods for the calculation of quadriceps force. In one method, the knee extensor moment was divided by the average of the lever arm of the four quadriceps components. In the other method, quadriceps force was estimated from the joint moments by minimizing a static cost function where the sum of squared muscle activations was related to maximum muscle strengths at each time step [16]. In the studies by Escamilla et al. [15,28,71], quadriceps, hamstring and gastrocnemius muscle force calculations were mentioned as a step necessary for the PFJ reaction force calculation. The authors mentioned that these calculations were made by means of computer optimization and it is not clear whether co-contraction adjustments were conducted.

3.2.3. Relationship between quadriceps force and PFJ reaction force

One study [23] reported the calculation of this coefficient directly from their sample, with the remaining studies mentioning that this coefficient had been extracted from previously published data and used to develop the formulas presented in Table 2. Seven studies [15,28,33,43,44,47,71] did not clearly present calculations of the coefficient *k*, however they referenced the study by van Eijden et al. [9] in their procedures, which suggests that the coefficient *k* calculation might have been conducted.

Three studies [9,10,82] were used as source for the calculation of the coefficient *k* or to develop the formula for the calculation; however, most studies reported having used data from the study by van Eijden et al. [9] to develop an equation to calculate the coefficient *k*.

Some differences among the formulas used to calculate the coefficient *k* were identified (Table 2). Compared to formula 1, which was used by the majority of the included studies, formula 2 presented a different positive sign, formula 3 presented an extra exponential function and formula 4 did not present a part of the formula (Table 2). Authors were contacted to confirm the differences in the formulas. The formulas presented in Table 2 were confirmed by the authors, with the exception of formula 3 and 4.

3.2.4. PFJ reaction force

In order to calculate PFJ reaction force, most studies multiplied the quadriceps muscle force by the coefficient *k* value (Table 3).

3.2.5. PFJ contact area

Seven studies measured PFJ contact area directly from their respective sample [6,19,23,26,59,64,65]. These studies used MRI images for these measurements. One study did not provide a clear description of this measurement [74]. The remaining studies reported the use of previously published data (Table 4). Three studies [16,48,73] combined data from more than one study for PFJ contact area calculation (Table 4). Kernozek et al. [16] combined data obtained by Powers et al. [30] and Connolly et al. [29]; Hofmann et al. [73] combined data obtained by Salsich et al. [84] and Huberti and Hayes [85]; and Herrington et al. [48] combined data obtained by Besier et al. [86], Lee et al. [87], Powers [88] and Salsich and Perman [89].

3.2.6. PFJ stress

All included studies divided PFJ reaction force by PFJ contact area, with the exception of the study by Peng et al. [74] and by Simpson et al. [7]. Peng et al. [74] only mentioned that the calculations followed the recommendations by Wirtz et al. [41], and Simpson et al. [7] mentioned that they used a cubic spline interpolative routine to obtain PFJ

Table 2
Summarized methods to calculate coefficient *k*.

Used method	*Study that cited the respective method*
$k = (-3.84E-05\times^{2} + 1.47E-03x + 0.462)/(-6.98E-07\times^{3} + 1.55E-04\times^{2} - 0.0162x + 1)$ [*Formula 1*][a]	[6,13,14,16,18,19,25,26,45,46,49,50,52–58,61–63,66,68–70,72,75]
$k = (-3.84E-05\times^{2} + 1.47E-03x + 0.462)/(-6.98E-07\times^{3} + 1.55E-04\times^{2} + 0.0162x + 1)$ [*Formula 2*]	[12,59,64]
$k = (-3.84E-05\times^{2} + 1.47E-03\times^{2} + 0.462)/(-6.98E-07\times^{3} + 1.55E-04\times^{2} - 0.0162x + 1)$ [*Formula 3*]	[40]
$k = (\mathbf{1.47E-03\times^{2} + 0.462})/(-6.98E-07\times^{3} + 1.55E{-}04\times^{2} - 0.0162x + 1)$ [*Formula 4*]	[48]
Formula is not presented, the only information given is the reference of previous study related to the coefficient *k* calculation [9]	[15,28,33,43,44,47,71]
Formula is not presented, but the coefficient *k* calculation is mentioned	[8,17,32,41,42,51,60,67]
Measure directly from their sample using MRI	[23]
No mention about coefficient *k* calculation	[7,65,73,74]

x: knee flexion angle.
[a] Differences in relation to the formula 1 are highlighted.

Table 3
Summarized methods to calculate PFJ reaction force.

Used method	*Study*
Multiplication of the quadriceps muscle force by the *k* coefficient	[6,8,12–14,16–19,25,26,32,40–42,45,46,48–64,66–70,72,75]
PFJ reaction force considering quadriceps force as a function of the knee flexion angle, based on the studies by van Eijden et al. [9,79]	[33,43,44,47]
Multiplication of the quadriceps force by the joint compression force/quadriceps force ratio from the sample of the study	[23]
Formulas presented by Sharma et al. [83], which considers the body mass of the participants and the knee flexion angle	[65]
PFJ reaction force calculated as a function of patellar tendon force and quadriceps tendon force	[15,28,71]
Algorithm in which patellar tendon force data and the angle formed by the force vectors of the quadriceps and patellar tendons are used to calculate PFJ reaction force	[7]
PFJ reaction force estimated as a function of knee angle and knee extensor moment	[73]
No explanation given	[74]

PFJ: patellofemoral joint.

stress from kinematic, kinetic and PFJ contact area data. Whyte et al. [19] presented not only the total PFJ stress, but also the medial and lateral PFJ stress results.

3.3. PFJ stress results

Regardless of the method used to calculate the PFJ stress among all the included studies, the greatest PFJ stress value (55.03 MPa) was obtained in the study performed by Simpson et al. [7] assessing a dance jump. The lowest PFJ stress value (1.9 MPa) was obtained in the study performed by Ho et al. [60], assessing healthy people during walking at the speed of 1.4 m/s wearing low heel shoes. Table 5 presents maximal, minimal and the range of PFJ stress for similar activities (running, walking, squatting and jumps) and populations among studies. Results from interventions were not considered. The individual PFJ stress results are presented in detail on Supplementary material 6 (Table).

Table 4
Summarized methods to calculate PFJ contact area.

Study	*Developed formula*	*Study used in calculation or formula development (participants in the used study)*
[18]	$CA = 2.0E-05\times^{4} - 0.0033\times^{3} + 0.1099\times^{2} + 3.5273\times + 81.058$	[30] (Six cadavers)
[13,17,25,32,40,45,49,51–58,60–62,66,67,69,72,75]	Formula is not presented	
[14,16,46,50,63]	$CA = 0.0781\times^{2} + 0.6763\times + 151.75$	[29] (10 healthy women and 10 women with PFP)
[41,42]	Formula is not presented	
[16]	$CA = -0.0001\times^{3} - 0.0082\times^{2} + 3.5071\times + 73.81$	[29,30] (above)
[15,28,71]	0°–60° knee flexion = $3.55\times + 135$ 70°–90° knee flexion = $2.81\times + 176$	[84] (10 healthy subjects)
[70]	Formula is not presented	
[33,43,44,47]	Formula is not presented	[90] (16 healthy subjects - 8 men and 8 women)
[8,12]	Formula is not presented	[85] (12 cadavers)
[68]	Formula is not presented	[89] (21 subjects with PFP and 21 healthy subjects)
[7]	Formula is not presented (data of lateral PFJ facet was used)	[91] (22 knees from cadavers)
[73]	Formula is not presented	[84,85] (above)
[48]	Formula is not presented	[89] (above), [86] (simulation study: 1 healthy subject), [87] (6 cadavers), [88] (narrative review)
[6,19,23,26,59,64,65]	PFJ contact area measured directly from their respective sample	

CA: Contact area; PFP: patellofemoral pain; PFJ: patellofemoral joint.

Table 5
PFJ stress results – Maximal, minimal and range by activities and populations (values in MPa).

Activity	Population	Values		Observation	Range
Running	Healthy	Max	21.5 [51]	Controlled speed of 3.4 m/s	15.60
		Min	5.90 [44]	Controlled speed of 3.5 m/s	
	PFJ pain	Max	11.60 [45]	Controlled speed of 4.0 m/s	3.60
		Min	8.00 [40]	Self-selected speed of 3.0 m/s	
Walking	Healthy	Max	4.36 [17]	Fastest speed of 1.95 m/s	2.39
		Min	1.97 [6]	Self-selected speed of 1.4 m/s	
	PFJ pain	Max	6.61 [6]	Fastest speed of 1.8 m/s	4.21
		Min	2.40 [59]	Self-selected speed of 1.3 m/s	
Squatting	Healthy	Max	13.06 [72]	Loaded squat – 35% of BW	7.50
		Min	5.56 [66]	Loaded squat – 40% 1RM	
Jumping	Healthy	Max	55.03 [7]	90% of maximal distance jump	28.32
		Min	26.71 [75]	Drop jump	

PFJ: patellofemoral joint; Max: maximal values; Min: minimal values; BW: body weight; RM: repetition maximum.

4. Discussion

After analyzing the PFJ stress results reported by the included studies, a large variability was noticed. For example, studies with similar activities and population presented PFJ stress differences larger than 15 MPa for the running activity in healthy people. These results are alarming, because the variability noticed in the present review is greater than the difference in PFJ stress presented by studies comparing healthy and affected populations [6,17]. Brechter and Powers [6] reported that people with PFJ pain had greater PJF stress compared to healthy people during fast walking. The difference between groups was approximately 4 MPa. It is evident that the used method may be the reason for the variability in PFJ stress results. The study which presented the greatest value used a method that is not comparable to other included methods [7]. Nevertheless, similar methods may result in discrepant values. Bonacci et al. [18] and Sinclair [56] assessed running in healthy people at the speed of 4.5 m/s and 4.0 m/s, respectively. Bonacci et al. [18] and Sinclair [56] used exactly the same method to calculate PFJ stress and for their control condition (wearing conventional running shoes) the peak PFJ stress results were 20.6 MPa and 10.3 MPa, respectively. This shows the potential divergence that the methods to calculate PFJ stress may present and highlights the need for consistent and accurate PFJ stress measurement.

The present study's main purpose was to systematically review the methods for calculating PFJ stress, in order to verify the best method for these calculations. However, it is not possible to determine which form of calculation is the best because there is no gold standard method for comparison and no study was developed to validate and compare the different methods. Despite the many physiological and biomechanical issues regarding in vitro studies, PFJ stress assessed in vitro directly in PFJ [92] could be used as a "standard", or at least as a starting point, to compare with PFJ stress obtained using indirect methods. However, caution is necessary since in vitro studies are unlikely to replicate the same forces a knee experiences in real life.

Considering that indirect methods have many steps and each step has its own assumptions and errors, when designing future studies, authors should carefully consider the methods most appropriate to the level of available data. It is also important to clearly describe the methods used (data collection and formulas) for the respective PFJ stress calculation. These careful considerations might facilitate comparison among studies.

The adjustment of sagittal plane forces is an important advancement in PFJ kinetic studies [32,33,43,44,47,51,67]. Among the included studies, two distinct ways of adjustment were identified: 1) the use of joint moments and lever arms and cross-sectional area of the knee flexor muscles from the literature [33,43,44,47]; 2) the use of kinematic and electromyographical data of the knee flexor muscles and other related variables from participants [32,51,67]. Both methods introduce further indirect calculations in the model, which might significantly influence the results for PFJ stress. Perhaps, the need for adjustments should also be evaluated, since the studies that did not include the adjustment have found similar results to those that did. Examples of this can be seen in a direct comparison of the results obtained during running in the studies by Bonacci et al. [18] and Teng and Powers [51], both with healthy participants. Bonacci et al. [18] did not perform the adjustment and obtained a PFJ stress value of 20.6 MPa. Teng and Powers [51] have adjusted the forces and found a PFJ stress value of 21.5 MPa.

Among the included studies, PFJ contact area measurement was the step that showed greater variability. PFJ contact area data was obtained from cadavers, from healthy subjects and subjects with PFJ pain from previous studies and directly from the respective study sample. Considering the difficulties in measuring contact area from a study sample, the use of previously published data seems to be a valid option. Still, this option requires attention, because several factors might influence PFJ contact area. For example, the procedures in which PFJ contact area was measured in previous studies might not properly reflect the PFJ contact area during dynamic activities. Some in vitro studies reported that PFJ contact area may change under load and load direction is another important aspect which can influence PFJ contact area [30,93]. Therefore, the load to which the PFJ is submitted during dynamic activities that involve vigorous muscle contraction, such as running, is probably greater than the one that occurs in static positions, even if there is axial load during the static measurements. Another important aspect that might not represent the dynamic task appropriately is the range of motion in which PFJ contact area is measured. As an example, the two most frequently cited studies have measured PFJ contact area at every 15°, from 0° to 75° [30] and from 0° to 45° [29] of knee flexion. This range is smaller than the range of knee flexion of some of the evaluated activities, such as the squat. Data interpolation is a mathematical method used to minimize the impact of this lack of available data for some of the knee higher ranges investigated in some studies; however, this is still a limitation and should be considered in future studies.

The specificity of the participant's characteristics regarding PFJ contact area also seems to be important. Connolly et al. [29] have shown that differences exist in PFJ contact area between healthy women and women with PFJ pain; and when comparing their data to that from Powers et al. [30], a study looking at PFJ contact area in cadavers, there is a difference of more than 100 mm^2 of PFJ contact area between the studies. In this context, standardization of PFJ contact area calculation might be necessary for a more adequate comparison between studies.

There were also variations in methods to calculate the coefficient k. Although most studies reported using data from van Eijden et al. [9] to calculate k, four variations in the formula were seen among studies. Because of the variations presented (Table 2) we ran the calculation of the k coefficient using the different methods found. The results of the simulation showed that the closest results to van Eijden et al. [9] were seen when using the formula 1: $k = (-3.84E-05 \times^2 + 1.47E-03x + 0.462)/(-6.98E-07 \times^3 + 1.55E-04 \times^2 - 0.0162\times + 1)$ (see Fig. 1, Supplementary material 7). Even though the variations should have had a large impact in the results for PFJ stress according to our simulation, that large impact was not present when analysing the results from these different studies. Perhaps, the variation in formulas seen among studies are simply typos introduced during the production of the manuscript; in which case all studies would have used the same formula when calculating the coefficient *k*. This shows the importance of rigor when checking manuscripts before publication, as simple typos as these could ultimately lead to mistakes in clinical interpretation.

After the simulations regarding the coefficient *k* calculation, we noticed that there was little explanation on the development of the formulas for the calculation. These formulas were extracted from a figure [9] and, therefore, might present some variability from the actual values. Considering that the variability is unknown and the used formulas are complex, we developed a new equation, also based on the study by van Eijden et al. [9] to provide a new option to calculate the coefficient *k*, in which we took into account the possible variability of the coefficients: $k = 2.70\mathrm{E}-02 \times^4 + 1.96\mathrm{E}-02 \times^3 - 0.15 \times^2 + 0.13\times + 0.97$ (x = normalized knee flexion angle). In the Supplementary material 7 (see Handout, Supplementary material 7) we present the methods used to develop the new equation and the possible variability of each segment of the equation.

Based on the present results, an important limitation of the methods used for PFJ stress calculations is the consideration of knee sagittal plane forces alone. During lower limb movements, patella moves in all three planes, which means forces in the three planes influence PFJ stress. The relevance of patellar movements is reinforced when PFJ dysfunctions are considered. Studies suggested that patellar kinematics and morphology have relation with pain in people with PFJ dysfunctions [94,95]. Future methods should consider frontal and transverse plane forces for a more comprehensive understanding of PFJ kinetics.

Clearly, the calculation of PFJ stress is complex, and consequently, its clinical applicability may be controversial. However, although clinicians are not expected to calculate PFJ stress, it is important that they are able to interpret the results from studies on PFJ stress. For that, clinicians should understand which involved factors in the calculation have the most influence on PFJ stress results. Examples are the PFJ contact area and forces acting on sagittal plane. Variations in PFJ contact area could explain variation on PFJ stress as Powers et al. [59] presented that an increase in PFJ contact area caused by wearing knee brace also caused a decrease in PFJ stress. Additionally, the choices made by researchers on which set of data to use when calculation PFJ contact area can also have an effect in the results. For example, two studies with similar methods to calculate PFJ stress during running, except for PFJ contact area calculation, in a similar population presented approximately 8 MPa of difference between the studies [25,46]. Another important factor in PFJ stress calculation is the sagittal load acting on knees. Again, two studies that tested interventions during running aiming to reduce the load on lower limbs (running barefoot and in a flexed trunk position) [18,51] found that such interventions reduced the load on knees (lower knee extensor moment). Consequently, the reduced load lead to a reduction in PFJ stress magnitude [18,51]. Therefore, it seems that clinicians, when intervening to reduce PFJ stress, should focus on exercises and techniques to reduce the load on lower limbs and/or to increase PFJ contact area. However, caution needs to be applied when analysing studies on PFJ stress, because the formulas used in the studies are generally different, making comparison between studies occasionally inappropriate.

5. Conclusion

PFJ stress calculation used by the majority of the studies has many indirect calculations; however methods with more data from participants might be preferred as direct measures are more likely to minimize the potential errors in the indirect calculations. When direct measures are not possible, based on the studies analyzed in the current systematic review, the model that seems to be the most appropriated is:

- *Quadriceps Muscle Effective Lever Arm* (L_{eff}) = $8.0\mathrm{E}-05x^3 -0.013x^2 + 0.28x + 0.046$;
- *Quadriceps Muscle Force* = knee extensor moment divided by L_{eff} (adjustment might be considered);
- *Coefficient k* = $(-3.84\mathrm{E}-05x^2 + 1.47\mathrm{E}-03x + 0.462)/(-6.98\mathrm{E}-07x^3 + 1.55\mathrm{E}-04x^2 - 0.0162x + 1)$;

or the new approach:

- *Coefficient* $k = 2.70\mathrm{E}-02x^4 + 1.96\mathrm{E}-02x^3 - 0.15x^2 + 0.13x + 0.97$;
- *PFJ Reaction Force* = Quadriceps Muscle Force versus coefficient *k*;
- *PFJ Contact Area* = direct from participants or consider participant's specificity; however, further investigation is needed;
- *PFJ Stress* = PFJ Reaction Force divided by PFJ Contact Area

Conflicts of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gaitpost.2017.12.018.

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