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Frontal plane leg alignment and muscular activity during maximum eccentric contractions in individuals with and without patellofemoral pain syndrome

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Abstract

Purpose: The role of frontal plane tibiofemoral alignment in subjects with patellofemoral pain syndrome (PFPS) is controversial and rarely discussed in the literature. As well, little research has been done on the effects of the hamstrings muscles on PFPS. The aim of the current study was to determine whether, in individuals with PFPS, frontal plane tibiofemoral alignment or muscular activity of the index knee's crossing muscles is altered during maximum eccentric leg press exercise.
Methods: This cross-sectional study involved 19 patients with PFPS and 19 control subjects who were matched according to gender, age, and physical activity. During eccentric leg press action, frontal plane tibiofemoral alignment was assessed with a motion analysis system based on skin markers. Simultaneously, surface-electromyography was used to assess the activity levels of the relevant knee crossing muscles. To assess the activity under functional conditions, a leg press with a footplate having variable stability was used for barefoot testing.
Results: The PFPS subjects did not have significantly different frontal plane leg alignment compared to controls. On electromyography (EMG), PFPS patients had significantly lower levels of hamstring activity during eccentric leg exercise. The differences between the two groups (%; absolute differences normalized EMG) ranged from 20% (semitendinosus; stable footplate; $p=0.017$) to 21% (biceps femoris; unstable footplate; $p=0.019$) and 32% (semitendinosus; unstable footplate; $p=0.002$).
Conclusions: PFPS is not linked to altered frontal plane leg alignment during eccentric leg pressing. However, PFPS is associated with eccentric under-activation of the hamstrings, which may be a compensatory strategy that maintains patellofemoral joint pressure within bearable levels.

Keywords: Patellofemoral; Alignment; Hamstrings; Valgus; Varus

1. Introduction

Patellofemoral pain syndrome (PFPS) is characterised by diffuse retro- or peripatellar pain for which there is no specific or definitive diagnosis [1,2,3]. It is aggravated by activities that require high quadriceps exertion such as stair climbing, squatting, running, or jumping [1,3] and is known to be one of the most prevalent disorders seen in orthopaedics and sports medicine [4–7].

The relationship of muscular interaction and PFPS has been studied. However, there is controversy over the role of the quadriceps with respect to the balance (timing and/or activity) between the vastus lateralis (VL) and the vastus medialis oblique (VMO) muscles [1,8–10]. Few studies have considered this matter in terms of the influence that hamstring activity has on patellofemoral conditions [11,12]. This may be due to the

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fact that the hamstring muscles directly influence tibiofemoral kinematics rather than patellofemoral kinematics. However, it has been shown that secondary movements of the tibiofemoral joint also influence the patellofemoral joint [12–14]. Studies that have concentrated on the effect of hamstring activity on the patellofemoral joint have shown that the duration of hamstring activity was increased among PFPS subjects [11].One study found that quadriceps/hamstrings co-contraction led to higher patellofemoral contact pressure than quadriceps contraction alone [12]; although these results were obtained *in vitro*, they suggest that the *in vivo* level of hamstring activity might be decreased among PFPS subjects in order that patellofemoral contact pressure be maintained within bearable limits.

The Q-angle is the link that connects patellofemoral kinematics and tibiofemoral alignment [14]. Given this, several studies have analyzed frontal plane tibiofemoral alignment (knee valgus and varus) in the context of PFPS [15–20]. There is evidence both for [15,16] and against [20] an association between frontal plane tibiofemoral malalignment and PFPS. These inconsistent results could be due to different functional conditions during alignment assessment, which have included supine static testing [20] and standing static testing [15,16]. Furthermore, other investigators, who adopted a functional testing approach during jumping [17] and running [18], did not perform statistical tests [17] or did not identify results of statistical significance [18].

Brouwer et al. assessed tibiofemoral alignment in patients with tibiofemoral osteoarthritis using standing and supine whole leg radiographs. They found that the more functional standing conditions resulted in an average of 2 degrees more varus [21]. Given these results, it is possible that PFPS subjects exclusively exhibit altered frontal plane tibiofemoral alignment under dynamic and functional conditions in comparison to control subjects. Frontal plane tibiofemoral alignment, other than in PFPS, has often been determined using functional methods during one leg standing [21–23], walking [24] or jumping [25].

It has been shown that functional test conditions reveal subtle neuromuscular alterations among PFPS subjects and can be done by challenging the subject's ability to stabilise adjacent body segments [1], as well as by barefoot testing [18]. Furthermore, it has been reported that eccentric contractions might reveal an altered neuromuscular pattern in PFPS subjects [9,26–28]. Thus, a functional methodological approach incorporating these ideas was used to verify the hypotheses that PFPS subjects have altered frontal plane leg alignment, different levels of leg extension strength, and different levels of muscular activity of the lateral and medial hamstrings compared to healthy controls.

2. Materials and methods

2.1. Participants

Nineteen participants (11 female, eight male) with PFPS of either the right or both knees were recruited from the Department of Orthopaedics. Patients were included if they met the following inclusion criteria: 1) history of retro- or peripatellar pain during physical activities including jumping, squatting, running, or stair ambulation, or after prolonged sitting with flexed knees; 2) the presence of at least one of the following clinical signs [20]: tenderness on palpation or compression of the patella, pain on isometric quadriceps contraction against suprapatellar resistance, pain on resisted knee extension; 3) non-traumatic onset of symptoms; 4) negative findings on clinical examination of the knee ligaments, menisci, bursae, and the tendons and their insertions surrounding the knee [2]. The exclusion criteria were: 1) previous knee surgery; 2) history of patellar dislocation; 3) age $\geq$40 years; 4) metabolic or rheumatic diseases affecting the musculoskeletal system; 5) other systemic diseases that could affect the musculoskeletal system or sensorimotor performance; 6) PFPS of singly the left knee. In addition, the knees were examined radiologically (anterior–posterior, lateral, and tangential images) to exclude osteoarthritis and tumors. Nineteen control subjects (11 female, eight male) with no history or symptoms of PFPS or any history of other knee disorder were recruited from among students and acquaintances of the investigators. Control subjects were excluded if they had any of the above-listed exclusion criteria, but radiographs were not obtained.

The groups were matched according to gender, age, height, body mass, and physical activity (Tables 1 and 2). The latter parameter was ascertained using the International Physical Activity Questionnaire (IPAQ) (short form for self-administration), which is a reliable and recommended tool for assessing activity status [29,30]. Furthermore, to verify proper assignment to a group, all subjects were additionally assessed using the Kujala score [31], which is one of the most valid and reliable tools for assessing patellofemoral pain [3]. Out of a total score of 100, PFPS patients had a median score of 85, whereas the control median Kujala score was 100 (Table 1), which was in agreement with previous research [31,32].

2.2. Procedures

The Ethics Committee at the Medical University approved the study, and informed consent was obtained from all subjects prior to participation.

Surface electromyography (EMG) involved standard skin preparation, checking electrical impedance (0), and placing pairs of Ag–AgCl electrodes over the bellies of the following muscles: vastus lateralis (VL), vastus medialis oblique (VMO), biceps femoris (BF), semitendinosus (ST), peroneus longus

Table 1
Participant characteristics of age, weight, height and Kujala score

	PFPS				Control			
	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum
Age (yr)	25.2	4.1	20	37	25.7	3.9	20	35
Weight (kg)	66.1	14.0	52	94	66.9	11.0	50	85
Height (m)	1.74	0.10	1.56	1.86	1.77	0.08	1.63	1.95
	Median	IQ-range	Minimum	Maximum	Median	IQ-range	Minimum	Maximun
Kujala score	85	14	71	94	100	0	98	100

SD: standard deviation, IQ-range: Interquartile-range.

Table 2
Participant characteristics of physical activity (category 1: inactive; category 3: highly active)

		PFPS	Control
Category 1	Number	4	2
	% of group	21.05	10.53
Category 2	Number	14	15
	% of group	73.68	78.95
Category 3	Number	1	2
	% of group	5.26	10.53
Total	Number	19	19
	% of group	100	100

IPAQ: international physical activity questionnaire.

(PL), and gastrocnemius medialis (GM). The electrode centre-to-centre distance was 34 mm and electrode placements were based on previous studies [1,33]. A Noraxon Myosystem 2000 (Noraxon, Scottsdale, Arizona) was used to obtain raw EMG signals.

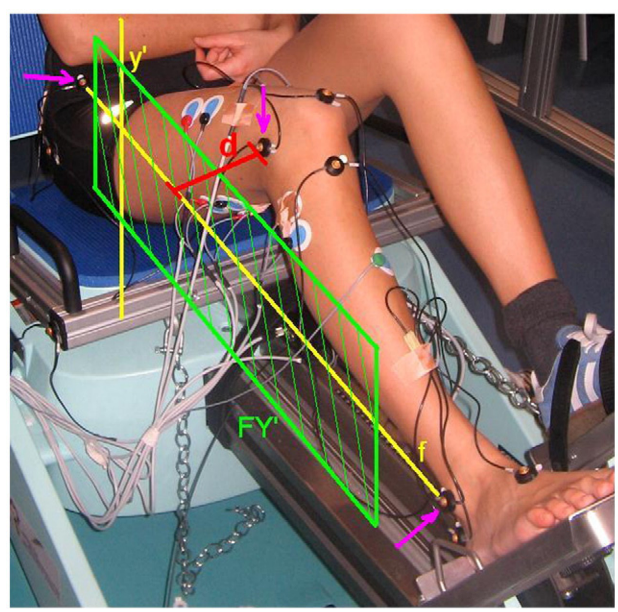
After a standardized warm-up, subjects were positioned in a force-measuring leg press system (CON-TREX, CMV AG, Duebendorf, Switzerland), which was recently described by Gardetto et al. [34]. The barefoot right leg, which was the symptomatic leg in the PFPS subjects, was tested. Active infrared skin markers from a motion analysis system (LUKOtronic AS 200, Lutz-Kovacs-Electronics, Innsbruck, Austria) were attached to the anterior superior iliac spine, greater trochanter, lateral femoral epicondyle, and lateral malleolus to obtain simultaneous two-dimensional motion analysis of the frontal and sagittal plane. Therefore, it was not possible to securely rule out influences of transverse plane movements. However, such two-dimensional approaches are commonly used to assess frontal plane leg alignment, especially in the field of PFPS [15–17,19,20,23,25,35]. Specifically, the precise three-dimensional kinematics of the lower body could not be assessed because of the inaccessibility of the posterior pelvis due to the patients' sitting position (also see below). The markers were always placed by the same investigator. The equipment has an accuracy of 0.7 mm and a precision of 0.015 mm, according to the manufacturer.

An initial measurement of the isometric maximum voluntary contraction (MVC) on leg pressing was done to guarantee normalization of the EMG data. This task was performed in 70° of knee flexion because medium knee flexion was reported to provide good patellar stabilization within the trochlear groove and data free from pain-related muscle inhibition [36]. Subjects then had to perform maximum eccentric quadriceps contraction against a stable footplate when it was moved towards them and to rest the leg passively on the footplate when it was removed (speed 0.2 m/s) (Fig. 1). This task was repeated six times. The reversal points of the automatic movement of the leg press footplate were standardized at 50° and 95° of knee flexion. After 5 min, the same task was performed with an unstable footplate, which permitted rubber-damped inversion and eversion of the ankle joint. This was done to simulate functional conditions by challenging the ability of the subjects to stabilise adjacent segments of the leg. A cross-over protocol was used, in that half of the subjects from both the PFPS and control groups completed a modified procedure with a changed sequence of stable and unstable footplates.

Fig. 1. Positioning of a participant in the leg press system. Electrodes and motion analysis markers were affixed to the right leg.

2.3. Data analysis

A custom-developed Matlab-routine (Matlab, The MathWorks Inc., Natick, Massachusetts, USA) was used for processing. The two-dimensional 'alignment distance' calculation was conducted as follows (Fig. 2): a plane (FY′) was calculated, containing a straight line (y') parallel to the system's y-axis (pointing upward) and a straight line (f) connecting the position of the anterior superior iliac spine and the lateral malleolus. From this plane, the perpendicular distance (d, 'alignment distance') to the position of the lateral femoral epicondyle was computed. The valgus and varus knee positions were indicated by negative and positive values, respectively. Analysis of frontal plane motion was two-dimensional and therefore sensitive to motion in the frontal as well as the transverse plane. Various factors, such as the contribution of femoral internal rotation to knee abduction, could not be ruled out by the use of the described methods. Precise three-dimensional assessment of the kinematics of the lower body could not be achieved because of the inaccessibility of the posterior pelvis due to the patients' sitting position. However, we calculated the alignment as a linear measure (distance; Fig. 2) instead of angles to exclude cross-talk between frontal plane alignment and knee flexion-extension, which was ascertained simultaneously in a two-dimensional manner via the greater trochanter, the lateral epicondyle and the lateral malleolus. We believe our two-dimensional approach of assessing frontal plane alignment is comparable to static [15,16,19,20] and dynamic [25] measurements of intercondylar



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distances. Our methods were also very similar to the dynamic two-dimensional frontal plane analyses performed by Nyland et al. [23], Sommer [17] and Willson et al. [35]. Ford et al [25] report between-day reliability ICC values > 0.893 for their method of dynamic alignment measurement. Nyland et al [23] also registered good reliability (ICC = 0.94) for their two-dimensional method. As these methods were very similar to ours we did not perform reliability measurements.

Force data was analyzed for the best three peaks from all six efforts and averaged. This was done for both the results obtained with the stable footplate and the results obtained with the unstable footplate to determine the variables 'Fmax stable' and 'Fmax unstable', respectively. Around each of the best three force peaks of a series, a window of 400 ms was centred for analysis as follows. The *mean* values of the three windows' 'alignment distance' were computed and regarded as one average value. This was done for the results obtained with the stable footplate as well as those obtained with the unstable footplate, to determine the variables 'mean alignment stable' and 'mean alignment unstable', respectively. The difference between these two variables was calculated to express the perturbational effect of the unstable footplate ('difference mean alignment').

Correspondingly, variables were computed to determine the *magnitude* of leg axis oscillations (*amplitude*): The amplitude of the 'alignment distance' was analyzed for each of the three windows described above. The average of these three values was used to determine the variables 'amplitude alignment stable' and 'amplitude alignment unstable' for stable and unstable series, respectively. Again, the difference between these two variables was calculated to express the perturbational effect of the unstable footplate ('difference amplitude alignment').

EMG data was digitally band pass filtered, and muscle activity was quantified with the 'root mean square (RMS)' method within the given window. The RMS-EMG reflects the mean power of a signal and is a commonly accepted method of analysis [37,38]. RMS-EMG was normalized to the initial maximum voluntary isometric contraction to make data comparable between subjects [39]. Normalized EMG data was regarded as the average of each test's three windows to arrive at stable and unstable variable values for the six tested muscles' activity.

The VMO and GM EMG data of one female participant in the control group were identified as incorrectly recorded; therefore, EMG data records of that subject were not included in the analysis. This data would have influenced the results to have greater statistical significance.

2.4. Statistical analysis

Based on the data available in the literature [40,41], we estimated that 15 subjects per group would be necessary to identify a 20% difference in leg extension strength at $\alpha = 0.05$ and $\beta = 0.20$. The data were processed with the Statistical Package for Social Sciences (SPSS-Norusis/SPSS Inc., Chicago, IL, USA). *P*-values < 0.05 were defined as statistically significant. Since variables were compared between the patient group and the control group and were, therefore, regarded as independent, *t*-tests for independent variables were used for variables with a normal distribution and Mann–Whitney U-tests were used for the others. Variables were accepted as normally distributed as determined by Kolmogorov–Smirnov-Tests (Lilliefors-corrected) and if no outlier was present on the Box-plot diagram.

3. Results

3.1. Force

Eccentric maximum force was significantly reduced in PFPS patients under both stable and unstable conditions. 'Fmax stable' was 1439 N in the patient group and 1757 N in the control group ($p = 0.032$). 'F max unstable' was 1322 N in the patient group and 1546 N in the control group ($p = 0.034$).

3.2. Alignment

Variables of the mean alignment of the legs are shown in Table 3. Both groups had a slight varus alignment; there were no significant group differences. In addition, when the variables dealing with the amplitude of alignment excursions (Table 3) were analysed, no significant differences between the groups were found.

The perturbational effect of the unstable footplate ('difference amplitude alignment') was more evident in the PFPS group (2.7 mm) than in the control group (0.9 mm); however, this difference was not statistically significant.

3.3. Muscular activity

There were no statistically significant differences between the PFPS subjects and controls in VL and VMO normalized activity, which was 106–109% for stable conditions and 102–104% for unstable conditions. However, there were significant differences between the groups for the hamstrings: PFPS subjects had semitendinosus normalized values of 81% under stable conditions and 81% under unstable conditions, compared to control values of 101% (stable, $p = 0.017$) and 113% (unstable, $p = 0.002$). The normalized activity of the biceps femoris was significantly different between the groups under unstable conditions (PFPS, 79% vs. controls, 100%; $p = 0.019$), but the difference did not reach statistical significance under stable conditions (PFPS, 85% vs. controls, 101%; $p = 0.105$). For the peroneus longus and gastrocnemius medialis muscles, PFPS subjects had consistently lower levels of normalized activity than controls, but the differences were not statistically significant (Table 4, Fig. 3).

During the measurements one female and one male subject in the PFPS group reported slight to moderate pain of typical character

Table 3
Alignment parameters of the PFPS group and control group

[mm]	PFPS				Control				Statistics
	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	*p* value
Mean alignment stable	9.5	15.1	−22.1	35.1	9.3	14.4	−16.3	40.1	0.863
Mean alignment unstable	8.9	15.3	−17.6	39.5	12.4	16.2	−23.1	43.7	0.504
Difference mean alignment	−0.6	9.6	−19.8	20.6	3.1	10.7	−13.4	23.6	0.271
Amplitude alignment stable	9.4	4.8	3.5	19.3	12.0	6.0	4.6	22.5	0.109
Amplitude alignment unstable	12.1	6.7	2.7	28.1	12.9	5.2	5.3	22.0	0.488
Difference amplitude alignment	2.7	5.5	−7.4	13.8	0.9	5.0	−8.5	8.8	0.279

(*SD*: Standard deviation; *Minimum*: lowest value measured; *Maximum*: highest value measured (range of data); *mean alignment stable/unstable*: mean value of the measured 'alignment distance' within a 400 ms time window; *amplitude alignment stable/unstable*: the magnitude of oscillation of the measured 'alignment distance' within a 400 ms time window; *difference mean/amplitude alignment*: difference between values of stable and unstable series to express the perturbational effect of the different footplates).

Table 4
Normalized muscular activity of PFPS group and control group

[%] Normalized muscular activity	PFPS				Control				Statistics
	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	*p* value
VL stable	109	17	83	139	107	23	69	151	0.809
VMO stable	106	15	83	138	107	25	75	153	0.982
BF stable	85	24	48	136	101	34	52	174	0.105
ST stable	81	22	54	129	101	29	64	185	0.017
PL stable	114	36	66	202	124	44	59	221	0.620
GM stable	109	41	46	207	130	56	74	317	0.271
VL unstable	104	16	77	137	103	19	70	140	0.867
VMO unstable	103	19	67	133	102	18	75	133	0.931
BF unstable	79	22	49	134	100	26	59	150	0.019
ST unstable	81	24	46	135	113	34	64	180	0.002
PL unstable	106	38	56	183	125	53	60	247	0.223
GM unstable	103	38	50	171	113	40	64	235	0.343

(VL = vastus lateralis; VMO = vastus medialis oblique; BF = biceps femoris; ST = semitendinosus; PL = peroneus longus; GM = gastrocnemius medialis).

between the two eccentric test series, but did not wish to abandon the procedure.

4. Discussion

Eccentric maximum force was found to be significantly lower in PFPS patients. In comparison to controls, the difference was 18.1% under stable conditions and 14.5% under unstable conditions. This is consistent with the literature [40,41], but it is the first time that functional eccentric testing has been done.

The results of the current study indicate that PFPS is not associated with altered frontal plane tibiofemoral alignment (valgus or varus) during functional eccentric contractions. These results are consistent with those of Witvrouw et al. [20], who prospectively proved that valgus or varus alignment was irrelevant etiologically. However, in that study, the alignment evaluation was assessed under static and non-weight bearing conditions. The findings of the current study differ from those of Lun et al. [15] and Milgrom et al. [16], who found that varus alignment was associated with PFPS. Frontal plane tibiofemoral alignment was also assessed under static and weight-bearing conditions (two-legged standing). It is difficult to draw conclusions based on these inconsistent findings, particularly since each study used different methods for assessing alignment. The measurement of frontal plane tibiofemoral alignment under functional conditions has been previously suggested [24,25], but it has not been implemented in studies involving PFPS patients prior to the present study. These measurement methods are important for detecting cases of altered tibiofemoral alignment that would not be identified in the supine position or during two-legged standing.

Among the potential weaknesses of the methods used for motion analysis, skin motion artefact and cross-talk between frontal- and transverse plane movements must be considered.

No clear conclusions can be reached about whether altered frontal plane tibiofemoral alignment contributes to the genesis of PFPS. In the future, prospective investigations should be done to determine baseline alignment of the lower extremity in a more functional and dynamic manner. Furthermore, a detailed description of the alignment measuring methods is required. Limitations of the current study's alignment measurement are the possible influences of transverse plane movements to those of the frontal plane. That could be excluded during future studies by adhering to the rules of concise three-dimensional motion analysis/marker models.

EMG results suggest that the hamstring muscles of PFPS patients have different neuromuscular patterns. The semitendinosus muscle was significantly less activated among PFPS patients with both stable and unstable footplates. The same result was demonstrated for the biceps femoris muscle, except that the results were statistically significant only under unstable conditions.

On further inspection of the data of muscle activation it is noticeable that the hamstrings/quadriceps ratio is relatively high (0.77 and 0.94 under stable conditions for PFPS patients and

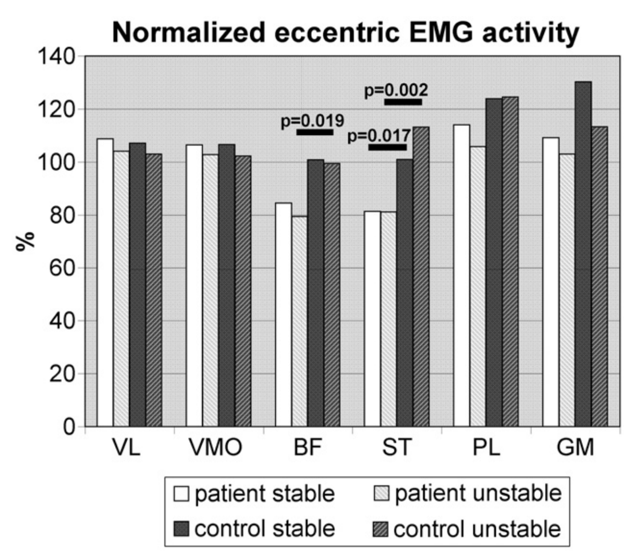

Fig. 3. Normalized muscular activity shows significantly lower levels for the hamstrings in PFPS subjects.

controls respectively). Maybe the reason could be that we took the MVC for quadriceps *and* hamstrings from a maximum effort of isometric leg extension. We considered our hamstrings MVC determination to be legitimate because the hamstrings not only flex the knee but also extend the hip — which was part of our MVC-leg extension. Potentially, future studies in the field of PFPS should consider to normalize hamstring MVC also separately during knee flexion.

No previous *in vivo* studies have dealt with the activity levels of the hamstrings in PFPS patients. Hess et al. [11] focused solely on the duration of hamstring activity in PFPS subjects during cycling and showed that they exhibited prolonged activity. An *in vitro* study by Li et al. [12] determined that the co-contraction of the hamstrings led to significantly increased levels of patellofemoral joint pressure in comparison to isolated quadriceps contraction. According to these authors, the hamstrings caused posterior tibial translation and, therefore, altered the parallelogram of forces acting on the patellofemoral joint.

At present, it is not clear whether this lower activity of the hamstrings should only be considered as the *effect* of PFPS or whether it should be considered to have *aetiological* significance. It has been shown that increased internal or external rotation of the shank leads to unbalanced patellofemoral load distribution and increased pressure [13,42]. Furthermore, Shultz et al. [43] demonstrated that the medial and lateral hamstrings use side-specific reflexes to respond to rotational perturbations of the knee and that, therefore, they act as controllers and stabilisers of both internal and external rotation of the shank. Therefore, the under-activation in PFPS patients could also have been part of a neuromuscular deficit that contributes to PFPS development. It is surprising that when the subjects of the current study were switched from stable to unstable conditions, the controls increasingly activated the semitendinosus (+12%, absolute difference), whereas the PFPS patients' semitendinosus activity remained unchanged. It is possible that the higher activation among controls reflected the neuromuscular response to the increased stress of knee stabilization.

Furthermore, one must consider whether PFPS patients have a higher risk of anterior cruciate ligament (ACL) injuries because of under-activity of the hamstrings, given that the hamstrings are known to protect the ACL [44].

In conclusion, we found that PFPS patients activated the hamstrings muscles less than controls during eccentric leg pressing. It remains to be determined whether this represents a compensatory neuromuscular pattern or an underlying etiological factor of PFPS, which leads to a lack of rotational knee stabilisation. No association was found between PFPS and altered frontal plane tibiofemoral alignment.

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