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Females with patellofemoral pain have impaired impact absorption during a single-legged drop vertical jump

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ABSTRACT

Background: Females with patellofemoral pain (PFP) have been reported to land with altered biomechanics in some, but not all studies. Kinematic alterations previously reported may indicate, and relate to potential impairments in absorbing impact.
Research question: To compare vertical ground reaction force (vGRF) and lower limb kinematics during single-legged drop vertical jumps in females with and without PFP; and establish the relationship between vGRF and kinematics during this task.
Methods: Fifty-two physically active females (26 with PFP and 26 controls) participated in the present cross-sectional study. Peak of vGRF was evaluated during landing; and lower limb kinematics in the sagittal and frontal planes during deceleration (landing) and acceleration (take-off) phases were evaluated.
Results: The PFP group had 11% greater vGRF ($p < 0.01$); and 13–24% lower hip, knee and ankle excursion in the sagittal plane during acceleration and deceleration phases ($p \leq 0.02$) compared to the control group. No significant between group differences ($p > 0.05$) for hip, knee and ankle excursion in the frontal plane were identified. Greater impact was significantly correlated with reduced knee ($r = -0.56$), hip ($r = -0.50$) and ankle ($r = -0.41$) excursion in the sagittal plane during the acceleration phase in the control group, but not in the PFP group. No significant correlations were found between vGRF and kinematics variables during the deceleration phase in either group.
Significance: Impaired ability to absorb load and reduced lower limb movement in the sagittal plane during landing in females with PFP may provide separate treatment targets during rehabilitation.

1. Introduction

Between 2007 and 2011, more than two million people were diagnosed with patellofemoral pain (PFP) in the United States [1]. PFP is an often persistent knee disorder [2], aggravated by tasks which load the patellofemoral joint, including sporting activities such as running and landing [3,4]. These activities are provocative due to associated high impact forces, which are estimated to be 3–5 times body weight during running [5] and single-legged drop landing [6].

Studies comparing impact generated (vertical ground reaction force – vGRF) during landing between people with and without PFP report conflicting findings. Willson and Davis [4] reported no difference between females with and without PFP during consecutives landings from a single-legged vertical jump. However, Peng et al. [7] reported that female ballet dancers with PFP have greater vGRF compared to asymptomatic controls during landings from a ballet related double-legged jump. Finally, Boling et al. [8] reported reduced vGRF during double-legged drop jump landing was associated with greater risk of developing PFP in their military cohort. Further research is needed to understand these inconsistent findings related to vGRF during landing in people with PFP, in order to guide development of interventions targeting impact absorption as part of rehabilitation.

Previous studies [4,7,8] have evaluated landing in people with PFP using different methods, which may explain inconsistencies in impact findings [6,9]. Drop vertical jump is frequently evaluated in studies to identify injury risk [8,10,11] and as a tool to assess patient's progress during rehabilitation [12]. Holden et al. [10] reported that increased knee valgus displacement during double-legged drop vertical jump from a 31 cm high box is a predictor factor for PFP development in adolescents. Single-legged drop vertical jumps have not been evaluated

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in people with PFP. In asymptomatic individuals, varying heights from 20 to 50 cm have been evaluated, producing between 2.8 and 5.3 times body weight [9]. Wang and Peng [9] suggest that single-legged drop jumps from 30 cm high box may be most appropriate for biomechanical benefits in plyometric training.

An impaired ability to control movements during landing may influence an individual's ability to absorb impact [13,14]. During landing from a single legged jump, females with PFP have been reported to possess altered hip movement control in the sagittal and frontal planes compared to asymptomatic controls, including greater hip adduction [15,16] and flexion [16]. However, other studies report no differences between groups when evaluating hip adduction [4,7,17] and flexion [7], as well as knee flexion [7,15,16] and ankle dorsiflexion [7]. Inconsistent hip kinematic results during jump landing [4,7,15–17] suggest further investigation is needed. Increased hip motion (related to dynamic knee valgus) is thought to relate to pain persistence due to increased lateral forces acting on patella and reductions in patellofemoral contact area [18]; subsequently increasing stress on the patellofemoral joint [19]. If females with PFP are unable to manage the forces during landing, it is important to know if kinematics is related to this potential deficit, which may provide new insights to target during rehabilitation programs. Additionally, kinematics during take-off from drop jump tasks has not been reported in previous studies of individuals with PFP, despite potential implications on performance and pain.

The primary aims of this cross-sectional study were to compare (i) vGRF; and (ii) joint excursion of the hip, knee and ankle in the sagittal and frontal planes during single-legged drop vertical jumps during landing and take-off between females with and without PFP. A secondary aim was to establish the relationship between vGRF and kinematic variables during single-legged drop vertical jumps. We hypothesized that females with PFP would have greater vGRF and movement of the hip, knee and ankle compared to asymptomatic females. We also hypothesized that vGRF and kinematics would be correlated for both groups.

2. Methods

2.1. Participants

Fifty-two physically active females (26 with PFP and 26 asymptomatic controls), between the ages of 18 and 35 from university community, gyms or recruited from social media participated (Table 1). Sample size was determined based on a pilot study of five participants in each group, using the vGRF results. Considering the difference of 0.4 N/N_{BW} between groups and the standard deviation of 0.5 N/N_{BW}, a minimum of 25 participants per group was required for an alpha of 0.05 and power of 80%. The study was approved by the Human Research Ethics Committee of São Carlos Federal University (registration number 40428514.6.0000.5504) and consent was obtained from all participants.

Table 1
Characteristics of participants (mean ± SD).

	PFP group (n = 26)	Control group (n = 26)
Age (years)	24.4 ± 4.2	22.8 ± 2.6*
Height (meters)	1.63 ± 0.06	1.65 ± 0.06*
Body mass (Kg)	59.5 ± 7.1	60.5 ± 7.1*
IPAQ (MET minutes/week)	3183.1 ± 2669.1	3198.8 ± 1555.3*
Pain onset (years)	4.7 ± 4.0	–
Symptoms duration (range)	6-180 months	–
Usual pain for jumping (VAS, 0-10)	4 ± 3	–
Pain level on testing day (VAS, cm)	1.6 ± 2.1	–
Pain level after test session (VAS, cm)	3.4 ± 2.5	–
Anterior Knee Pain Scale (points) [32]	73.4 ± 9.2	–
Pain Severity Scale (points) [32]	40.5 ± 17.9	–

* No significant difference between groups using independent *t*-test PFP: patellofemoral pain; IPAQ: International Physical Activity Questionnaire short form; [33] VAS: visual analogue scale.

To be included in the PFP group, participants had to have: i) insidious onset of symptoms unrelated to traumatic event; ii) presence of retropatellar or peripatellar pain; iii) minimum 3/10 points on VAS in at least three of the follow situations: stair negotiation, running, kneeling, squatting, prolonged sitting, jumping, isometric contraction of quadriceps, and palpation of the medial or lateral facet of the patella; iv) presence of pain for at least two months [20,21]. To be included in the control group, participants had to have no history of injury or pain in the knees, and present with similar anthropometric measures (age, height, and body weight) and level of physical activity to the PFP group [20,21]. For both groups, participants could not have history of knee surgery, hip pain or injury, patellar instability, pain on palpation of the patellar tendon area, Hoffa's fat pad, iliotibial band, pes anserinus tendon or knee joint line, signs or symptoms of meniscal or knee ligament injuries, presence of Osgood-Schlatter and Sinding-Larsen-Johansson syndrome [20,21].

2.2. Procedures

Assessments were performed in a single session. For the PFP group, the lower limb of the most painful knee was assessed. If the most painful knee was in the dominant lower limb, the dominant lower limb of the pair in the control group was assessed, and vice versa.

2.3. Single-legged drop vertical jump

The participants were instructed to keep their arms crossed over their chest, in single-legged stance, and drop forward onto a force place from a 31 cm high box [9,22], and upon landing, jump vertically as high and quick as possible. The participants were wearing shorts, sports bra and neutral shoes provided by assessors (Asics Gel-Equation5, Asics, ID). Five valid trials were captured with a minimum interval of one minute between trials. Participants were familiarized with the task at least twice before the data collection.

Kinematics were captured using a seven camera Qualisys Motion Capture System (Qualisys Medical, AB, SE) with a sampling rate of 240 Hz. vGRF was assessed using one force plate Bertec (4060-08, Bertec Corporation, OH, EUA) with a sampling rate of 2400 Hz. Both collection systems were integrated using the acquisition software Qualisys Track Manager 2.3 (Qualisys Medical, AB, SE). Eighteen retroreflective markers were positioned on each participant: spinous process of the seventh cervical vertebra, sternum, right and left acromium, the joint space between the fifth lumbar and the first sacral spinous processes, right and left iliac crest, posterior superior iliac spines, great trochanter of both femurs, lateral and medial femoral epicondyles, lateral and medial malleoli, first and fifth metatarsal heads, and distal phalange of the second toe. Five clusters were placed over: the spinous process of the fourth thoracic vertebra, the spinous process of the second lumbar vertebra, the posterolateral side of thigh, the posterolateral side of shank and calcaneus region.

2.4. Data analysis

Kinematic and kinetic data were processed using Visual 3D (version 3.9; C-motion Inc., USA). Cardan angles were calculated using the joint coordinate system relative to the static standing trial recommended by International Society of Biomechanics [23]. Hip, knee and ankle angles were calculated as the movement of the distal segment relative to the proximal segment. Kinematic and kinetic data were filtered using a fourth-order zero-lag Butterworth 12 Hz and 50 Hz low-pass filter, respectively.

Matlab software (version 2008b, Mathworks, Natick, USA) was used

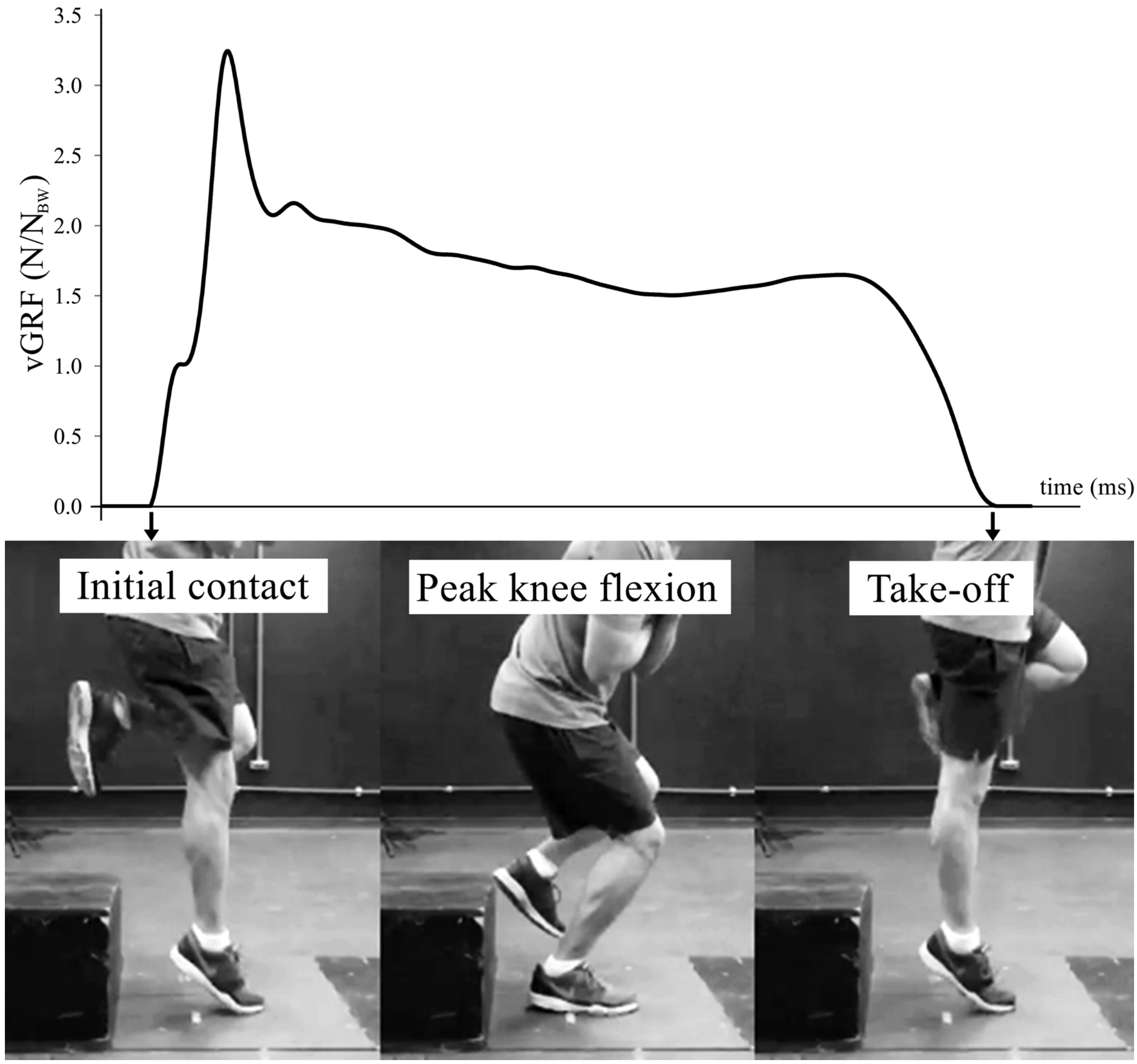

Fig. 1. Vertical ground reaction force (vGRF) graph and description of deceleration (from initial contact to peak knee flexion) and acceleration (from peak knee flexion to take-off) phases.

for data reduction. All data was analyzed during the contact phase from the foot initial contact to the take-off to perform the vertical jump. Initial contact was defined as the instant when vGRF exceed 10 N and take-off was defined as the instant when vGRF was again inferior to 10 N [24]. For the kinematic analysis, the contact phase was divided in deceleration and acceleration phases. Deceleration phase was from initial contact to peak knee flexion, and acceleration phase was from peak knee flexion to take-off (Fig. 1). Mean values from the five trials were used for analysis.

Eight participants (four each group) were evaluated on two separate occasions prior to the data collection with 3–7 days apart from the first assessment to verify the intra-rater reliability using intraclass correlation coefficient ($ICC_{3,1}$) and standard error of measurement (SEM). Variables of interest and their reliability results are:

- *Vertical ground reaction force (vGRF)*: peak of vGRF normalized by body weight (N/N_{BW}) [$ICC_{3,1}$ (SEM) = 0.92 (0.3 N/N_{BW})] (Fig. 1).
- *Joint excursion:* joint excursion during the deceleration and acceleration phases for hip, knee and ankle in the sagittal and frontal planes (degrees). Joint excursion for the deceleration phase was defined as the difference between peak angle during the deceleration phase and angle at initial contact; and joint excursion for the acceleration phase was defined as the difference between peak angle during the acceleration phase and angle at take-off [$ICC_{3,1}$ (SEM) = 0.78-0.92 (0.8–2.9 degrees)].

2.5. Statistical analysis

T test for independent samples was used to compare vGRF and the characterization data between the groups. Two-way mixed model analysis of variance (ANOVA) was used to compare the groups regarding kinematics data during deceleration and acceleration phases. Subsequent pairwise comparisons were made using Bonferroni correction. The effect size (ES – Hedges' g) was calculated using Review Manager (version 5.2, Copenhagen, Denmark) for each comparison. Pearson correlations were calculated to verify the association between vGRF and kinematic measures. Correlations were considered as: poor ($r = 0.00–0.25$), fair ($r = 0.25–0.50$), moderate to good ($r = 0.50$ to 0.75), and excellent ($r = 0.75–1.00$) [25]. The confidence level was set at 5%. Data were analyzed using SPSS version 17.0 (SPSS Inc., Chicago, IL, USA).

3. Results

Anthropometric measures and level of physical activity were similar between groups ($p > 0.05$) (Table 1).

Table 2
Kinematic for comparisons between groups (*mean ± SD)**.

	DECELERATION PHASE				ACCELERATION PHASE			
	PFP group	Control group	Mean difference (95% CI)	Effect size	PFP group	Control group	Mean difference (95% CI)	Effect size
Sagittal Plane								
Hip	18.4 ± 10.6	24.3 ± 6.9	−5.9 (−10.9 to -0.9)	**0.65**	34.7 ± 11.6	44.3 ± 10.1	−9.6 (−15.7 to -3.6)	**0.87**
Knee	43.8 ± 9.2	50.1 ± 7.0	−6.3 (−10.8 to -1.7)	**0.76**	46.8 ± 11.5	59.9 ± 11.2	−13.1 (−19.4 to -6.8)	**1.14**
Ankle	48.2 ± 9.0	52.2 ± 7.2	−4.1 (−8.6 to 0.5)[1]	0.48	46.4 ± 11.0	54.0 ± 7.5	−7.6 (−12.8 to -2.4)	**0.80**
Frontal Plane								
Hip	19.2 ± 4.7	19.6 ± 5.6	−0.3 (−3.2 to 2.6)	0.08	12.5 ± 5.2	13.9 ± 5.9	−1.4 (−4.5 to 1.7)	0.25
Knee	3.6 ± 3.3	4.7 ± 3.9	−1.1 (−3.1 to 0.9)	0.30	3.6 ± 3.3	4.1 ± 4.4	−0.6 (−2.7 to 1.6)	0.13
Ankle	13.7 ± 5.3	14.2 ± 4.8	−0.6 (−3.4 to 2.2)	0.10	12.4 ± 4.4	14.8 ± 4.9	−2.5 (−5.0 to 0.1)[1]	0.51

PFP: patellofemoral pain. Effect size in bold indicates significant differences. *Joint excursion in degrees. [1]statistical trends ($p < 0.08$).

3.1. Impact

The PFP group (4.6 ± 0.5 N/N_{BW}) had 11% greater vGRF compared to the control group (4.1 ± 0.4 N/N_{BW}) (mean difference 0.5 N/N_{BW}; $p < 0.01$; 95% CI 0.2–0.7; ES = 1.09).

3.2. Kinematics

During the deceleration phase, the PFP group had 13% lower knee flexion excursion ($p < 0.01$) and 24% lower hip flexion excursion ($p = 0.02$) compared to the control group (Table 2). During the acceleration phase, the PFP group had 22% lower knee extension excursion ($p < 0.01$), 22% lower hip extension excursion ($p < 0.01$), and 14% lower ankle plantar flexion excursion ($p < 0.01$) compared to the control group (Table 2). There were also statistical trends for reduced ankle excursion in the sagittal plane during the deceleration phase (8%, $p = 0.08$) and in the frontal plane during the acceleration phase in the PFP group (16%, $p = 0.06$) (Table 2). No difference between the groups was found for knee or hip excursion in the frontal plane during any phase; and for ankle excursion in the frontal plane during the deceleration phase (Table 2).

3.3. Correlations

In the control group, greater vGRF magnitude correlated ($p < 0.05$) with reduced knee ($r = –0.56$), hip ($r = –0.50$) and ankle ($r = –0.41$) excursion in the sagittal plane during the acceleration phase (Table 3). There were also statistical trends ($p < 0.09$) for correlations in the control group between greater vGRF magnitude and reduced knee and hip excursion in the sagittal plane during the deceleration phase (Table 3). No significant correlations were identified during both phases for the PFP group (Table 3).

Table 3
Correlations kinematics versus impact.

Kinematics		vGRF	
		PFP group	*Control group*
Deceleration phase	*Sagittal Plane*		
	Hip	−0.33	−0.38[1]
	Knee	−0.27	−0.34[1]
	Ankle	−0.26	−0.31
	Frontal Plane		
	Hip	−0.06	0.03
	Knee	−0.31	0.15
	Ankle	−0.06	0.23
Acceleration phase	*Sagittal Plane*		
	Hip	−0.22	**−0.50**
	Knee	−0.06	**−0.56**
	Ankle	−0.03	**−0.41**
	Frontal Plane		
	Hip	−0.08	−0.13
	Knee	−0.17	0.11
	Ankle	−0.01	−0.07

vGRF: vertical ground reaction force; PFP: patellofemoral pain. *r values in bold means significant correlations. [1]statistical trend ($p < 0.09$).

4. Discussion

Increased vGRF and reduced sagittal plane excursion at the knee and hip during landing found in this study indicates that females with PFP have impaired ability to control impact during single-legged landing compared to asymptomatic females. Additionally, reduced sagittal plane excursion of the ankle, knee and hip during acceleration into a jump among the PFP group also indicates impaired ability to take-off, which may detrimentally impact on performance. Together, these findings highlight the need for potential treatment strategies to improve load absorption during landing, and function during take-off in females with PFP.

Impaired load absorption during landing in our PFP group is consistent with findings reported by Peng et al. [7]. However, Willson and Davis [4] reported no difference between females with and without PFP regarding vGRF during landing. The task completed by Willson and Davis [4] involved repeated single-legged maximal jumps from the floor which led to variable landing height among participants. Specifically, the PFP group jumped significantly lower than the control group [4], which may have led to an absence of difference between groups in vGRF. Further research is needed to understand the influence of jump height on vGRF in people with PFP.

The cross-sectional nature of our study mean it is not possible to determine cause or effect in relation to differences in vGRF between groups. Interestingly, Boling et al. [8] reported reduced vGRF from jump landing was related to greater risk of developing PFP in their mixed-sex military population, which is contrary to our findings. A number of potential explanations require consideration. Firstly, Boling et al.'s [8] findings precede the onset of pain. Therefore, it is possible that impairments in the ability to absorb load occur over time due to the presence of pain and subsequent muscle weakness [21,26,27], rate of force development impairments [21], and kinesiophobia [28] which develop. Secondly, Boling et al. [8] evaluated a double-legged drop vertical jump, whilst we evaluated a single-legged drop vertical jump, which may influence the ability to absorb load in the presence of pain (Table 1). Thirdly, our study included a female non-military population, whilst Boling et al. [8] included a mixed-sex military population, which may influence findings. Sex differences between cohorts may be particularly relevant considering previously reported differences between sexes, including greater impairments in strength [29] and kinematics [30] among females with PFP. Further research is needed to explore the potential influence of each of these methodological differences on load absorption during landing tasks in people with PFP.

Our female PFP cohort landed with reduced joint excursion in the sagittal plane at the knee and hip, and did not have any aberrant frontal plane movement. This finding was unexpected and is contrary to previous studies which have reported females with PFP land and run with excessive hip adduction and internal rotation [3,4,15,17]. During landing specifically, females with PFP have been reported to possess greater hip adduction [15] and internal rotation [17]. The absence of a difference between groups for hip adduction excursion may be explained by the reduced sagittal plane excursion at the knee and hip during landing which we also observed in our PFP cohort compared to controls. This may reflect a strategy to protect the patellofemoral joint by reducing compressive loads associated with knee flexion, or avoiding hip adduction and knee valgus [12]. Supporting this notion, a previous study has reported that approximately 30% of the variance in hip adduction is explained by the peak knee flexion during stair negotiation [31]. Additionally, in a *post hoc* analysis of our data, we found a significant correlation between sagittal plane knee and frontal plane hip motion (r = 0.56). Therefore, it is possible that if people with PFP do not limit knee flexion during landing as found in our study, excessive hip adduction may occur, as reported by Willson and Davis [15]. Supporting this notion, Willson and Davis [15] reported no difference between groups regarding knee flexion range of motion.

Interestingly, we found vGRF was significantly correlated with sagittal plane excursion in the control group only. Additionally, this correlation occurred only during acceleration, with no significant relationships identified for either group during deceleration. This would indicate that impairment in ability to absorb impact during landing, may lead to a reduction in joint motion, and possibly impact on performance during take-off of a single-legged drop vertical jump in an asymptomatic female population.

Although both vGRF and kinematics were found to be different between the groups during landing, these apparent impairments do not appear to be correlated. This was surprising considering previous reports that increasing lower limb movement in the sagittal plane during landing is an effective intervention to reduce impact [13,14]. It is possible that some potential outliers from PFP group for both knee and hip correlations with vGRF impeded identification of a relationship. Regardless, our findings highlight the need to consider other factors which may explain impaired impact absorption during landing in females with PFP. Potential influences on vGRF worthy of consideration and potential intervention include muscle function and capacity including both strength and power, and fear of movement.

4.1. Clinical implications

A lack of significant relationship between landing (deceleration) kinematics and vGRF, in the presence of impairments in both, indicates a need to potentially target vGRF and kinematics of landing separately during rehabilitation. Our findings highlight the potential importance of strategies to reduce vGRF magnitude and subsequent patellofemoral joint loading during landing activities as part of PFP rehabilitation. Exercise therapy targeting hip and knee muscle function has been reported to improve biomechanics, function and pain related to running [3]. Although further research is needed evaluating the effects of exercise therapy on landing mechanics, similar exercise programs to those used in runners [3] may have therapeutic implications for landing based activities in females with PFP.

Reduced sagittal plane motion of the knee and hip may require specific movement pattern retraining during rehabilitation of females with PFP. Interestingly, it has been reported that females who are screened prospectively and go onto injure their anterior cruciate ligament (ACL) present similar landing impairments found in the PFP cohort in our study – i.e. high impact and lower knee motion during landing [11]. Therefore, addressing these deficits in females with PFP may also have implications for secondary injury prevention.

4.2. Limitations

This study's findings should be interpreted with consideration to four key limitations. First, the task evaluated might not exactly reflect common functional activities, but provides a standardised and controlled evaluation. Based on previous conflicting findings reported for landing mechanics in females with PFP, this standardisation appears to be important. Future studies should consider concurrently evaluating similar loading variables during tasks such as running, cutting and landing from sports specific tasks (e.g. taking a rebound in Basketball). Second, findings are limited to a young female adult population, with further evaluation needed in males and other age groups (adolescents and older adults). Third, the sample size was based on providing adequate statistical power for vGRF. However, the study may have been underpowered for some comparisons and correlations. Specifically, we found statistical trends for between group comparisons in sagittal and frontal plane ankle excursion, and for correlations between vGRF and knee/hip sagittal excursion during the deceleration phase in the control group. Fourth, we only evaluated if kinematics were related to altered impact during landing. Other outcomes, such as muscle activation (EMG), may explain greater vGRF found in our females PFP cohort. Further evaluation of factors which may influence impact absorption in females with PFP is needed.

5. Conclusion

Results from this study indicate young females with PFP have an impaired ability to absorb load during a single legged jump landing task compared to asymptomatic controls. This is reflected by a higher vGRF, combined with reduced knee and hip excursion in the sagittal plane. However, these impairments do not appear to be related. Development and evaluation of rehabilitation strategies to address deficits in load absorption capacity targeting both vGRF and kinematics in females with PFP is encouraged.

Conflict of interest statement

None.

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References

[1] N.R. Glaviano, M. Kew, J.M. Hart, S. Saliba, Demographic and epidemiological trends in patellofemoral pain, Int. J. Sports Phys. Ther. 10 (2015) 281–290.
[2] N.E. Lankhorst, M. van Middelkoop, K.M. Crossley, S.M.A. Bierma-Zeinstra, E.H.G. Oei, B. Vicenzino, N.J. Collin, Factors that predict a poor outcome 5-8 years after the diagnosis of patellofemoral pain: a multicentre observational analysis, Br. J. Sports Med. 50 (2016) 881–886, https://doi.org/10.1136/bjsports-2015-094664.
[3] B.S. Neal, C.J. Barton, R. Gallie, P. O'Halloran, D. Morrissey, Runners with patellofemoral pain have altered biomechanics which targeted interventions can modify: a systematic review and meta-analysis, Gait Posture 45 (2016) 69–82, https://doi.org/10.1016/j.gaitpost.2015.11.018.
[4] J.D. Willson, I.S. Davis, Lower extremity mechanics of females with and without patellofemoral pain across activities with progressively greater task demands, Clin. Biomech. 23 (2008) 203–211, https://doi.org/10.1016/j.clinbiomech.2007.08.025.
[5] X. Phan, T.L. Grisbrook, K. Wernli, S.M. Stearne, P. Davey, L. Ng, Running quietly reduces ground reaction force and vertical loading rate and alters foot strike technique, J. Sports Sci. 35 (2017) 1636–1642, https://doi.org/10.1080/02640414.2016.1227466.
[6] N.R. Heebner, D.M. Rafferty, M.F. Wohleber, A.J. Simonson, M. Lovalekar, A. Reinert, T.C. Sell, Landing kinematics and kinetics at the knee during different landing tasks, J. Athl. Train. 52 (2017) 1101–1108, https://doi.org/10.4085/1062-6050-52.11.25.
[7] H.-T. Peng, W.C. Chen, T.W. Kernozek, K. Kim, C.-Y. Song, Influences of patellofemoral pain and fatigue in female dancers during ballet jump-landing, Int. J. Sports Med. 36 (2015) 747–753, https://doi.org/10.1055/s-0035-1547220.
[8] M.C. Boling, D.A. Padua, S.W. Marshall, K. Guskiewicz, S. Pyne, A. Beutler, A

prospective investigation of biomechanical risk factors for patellofemoral pain syndrome: the Joint undertaking to monitor and prevent ACL Injury (JUMP-ACL) cohort, Am. J. Sports Med. 37 (2009) 2108–2116, https://doi.org/10.1177/0363546509337934.

[9] L.-I. Wang, H.-T. Peng, Biomechanical comparisons of single- and double-legged drop jumps with changes in drop height, Int. J. Sports Med. 35 (2014) 522–527, https://doi.org/10.1055/s-0033-1345133.

[10] S. Holden, C. Boreham, C. Doherty, E. Delahunt, Two-dimensional knee valgus displacement as a predictor of patellofemoral pain in adolescent females, Scand. J. Med. Sci. Sports 27 (2017) 188–194, https://doi.org/10.1111/sms.12633.

[11] T.E. Hewett, G.D. Myer, K.R. Ford, R.S. Heidt, A.J. Colosimo, S.G. McLean, A.J. van den Bogert, M.V. Paterno, P. Succop, Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study, Am. J. Sports Med. 33 (2005) 492–501, https://doi.org/10.1177/0363546504269591.

[12] S.S. Gagnon, T.B. Birmingham, B.M. Chesworth, D. Bryant, M. Werstine, J.R. Giffin, Development of a clinician-rated drop vertical jump scale for patients undergoing rehabilitation after anterior cruciate ligament reconstruction: a Delphi approach, J. Orthop. Sports Phys. Ther. 47 (2017) 557–564, https://doi.org/10.2519/jospt.2017.7183.

[13] J. Favre, C. Clancy, A.V. Dowling, T.P. Andriacchi, Modification of knee flexion angle has patient-specific effects on anterior cruciate ligament injury risk factors during jump landing, Am. J. Sports Med. 44 (2016) 1540–1546, https://doi.org/10.1177/0363546516634000.

[14] P. McNair, H. Prapavessis, K. Callender, Decreasing landing forces: effect of instruction, Br. J. Sports Med. 34 (2000) 293–296, https://doi.org/10.1136/bjsm.34.4.293.

[15] J.D. Willson, I.S. Davis, Lower extremity strength and mechanics during jumping in women with patellofemoral pain, J. Sport Rehabil. 18 (2009) 76–90.

[16] J.D. Willson, S. Binder-Macleod, I.S. Davis, Lower extremity jumping mechanics of female athletes with and without patellofemoral pain before and after exertion, Am. J. Sports Med. 36 (2008) 1587–1596, https://doi.org/10.1177/0363546508315592.

[17] R.B. Souza, C.M. Powers, Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain, J. Orthop. Sports Phys. Ther. 39 (2009) 12–19, https://doi.org/10.2519/jospt.2009.2885.

[18] R.B. Souza, C.E. Draper, M. Fredericson, C.M. Powers, Femur rotation and patellofemoral joint kinematics: a weight-bearing magnetic resonance imaging analysis, J. Orthop. Sports Phys. Ther. 40 (2010) 277–285, https://doi.org/10.2519/jospt.2010.3215.

[19] C.M. Powers, The influence of abnormal hip mechanics on knee injury: a biomechanical perspective, J. Orthop. Sports Phys. Ther. 40 (2010) 42–51, https://doi.org/10.2519/jospt.2010.3337.

[20] T.H. Nakagawa, É.T.U. Moriya, C.D. Maciel, A.F.V. Serrão, Frontal plane biomechanics in males and females with and without patellofemoral pain, Med. Sci. Sports Exerc. 44 (2012) 1747–1755, https://doi.org/10.1249/MSS.0b013e318256903a.

[21] G.S. Nunes, C.J. Barton, F.V. Serrão, Hip rate of force development and strength are impaired in females with patellofemoral pain without signs of altered gluteus medius and maximus morphology, J. Sci. Med. Sport 21 (2018) 123–128, https://doi.org/10.1016/j.jsams.2017.05.014.

[22] G.C. Lessi, F.V. Serrão, Effects of fatigue on lower limb, pelvis and trunk kinematics and lower limb muscle activity during single-leg landing after anterior cruciate ligament reconstruction, Knee Surg. Sports Traumatol. Arthrosc. 25 (2017) 2550–2558, https://doi.org/10.1007/s00167-015-3762-x.

[23] G. Wu, S. Siegler, P. Allard, C. Kirtley, A. Leardini, D. Rosenbaum, M. Whittle, D.D. D'Lima, L. Cristofolini, H. Witte, O. Schmid, I. Stokes, Standardization and terminology committee of the International Society of Biomechanics, ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion - part I: ankle, hip, and spine. International Society of Biomechanics, J. Biomech. 35 (2002) 543–548.

[24] M. Walsh, M.C. Boling, M. McGrath, J.T. Blackburn, D.A. Padua, Lower extremity muscle activation and knee flexion during a jump-landing task, J. Athl. Train. 47 (2012) 406–413, https://doi.org/10.4085/1062-6050-47.4.17.

[25] L.G. Portney, M.P. Watkins, Foundations of Clinical Research - Applications to Practice, 3rd ed., Appleton & Lange, Connecticut, 2009.

[26] M.S. Rathleff, C.R. Rathleff, K.M. Crossley, C.J. Barton, Is hip strength a risk factor for patellofemoral pain? A systematic review and meta-analysis, Br. J. Sports Med. (2014), https://doi.org/10.1136/bjsports-2013-093305.

[27] D. Kaya, S. Citaker, U. Kerimoglu, O.A. Atay, J. Nyland, M. Callaghan, Y. Yakut, I. Yüksel, M.N. Doral, Women with patellofemoral pain syndrome have quadriceps femoris volume and strength deficiency, Knee Surg. Sports Traumatol. Arthrosc. 19 (2011) 242–247, https://doi.org/10.1007/s00167-010-1290-2.

[28] L.R. Maclachlan, N.J. Collins, M.L.G. Matthews, P.W. Hodges, B. Vicenzino, The psychological features of patellofemoral pain: a systematic review, Br. J. Sports Med. 51 (2017) 732–742, https://doi.org/10.1136/bjsports-2016-096705.

[29] L.A. Bolgla, J. Earl-Boehm, C. Emery, K. Hamstra-Wright, R. Ferber, Comparison of hip and knee strength in males with and without patellofemoral pain, Phys. Ther. Sport 16 (2015) 215–221, https://doi.org/10.1016/j.ptsp.2014.11.001.

[30] R.W. Willy, K.T. Manal, E.E. Witvrouw, I.S. Davis, Are mechanics different between male and female runners with patellofemoral pain? Med. Sci. Sports Exerc. 44 (2012) 2165–2171, https://doi.org/10.1249/MSS.0b013e3182629215.

[31] D. de Oliveira Silva, C.J. Barton, M.F. Pazzinatto, R.V. Briani, F.M. de Azevedo, Proximal mechanics during stair ascent are more discriminate of females with patellofemoral pain than distal mechanics, Clin. Biomech. 35 (2016) 56–61, https://doi.org/10.1016/j.clinbiomech.2016.04.009.

[32] R.A. da Cunha, L.O.P. Costa, L.C. Hespanhol Junior, R.S. Pires, U.M. Kujala, A.D. Lopes, Translation, cross-cultural adaptation, and clinimetric testing of instruments used to assess patients with patellofemoral pain syndrome in the Brazilian population, J. Orthop. Sports Phys. Ther. 43 (2013) 332–339, https://doi.org/10.2519/jospt.2013.4228.

[33] R. Pardini, T. Araújo, V. Matsudo, E. Andrade, G. Braggion, Validation of the International Physical Activity Questionnaire (IPAQ version 6): pilot study in Brazilian young adults, Rev. Bras. Ciên. E Mov. 9 (2001) 45–51.